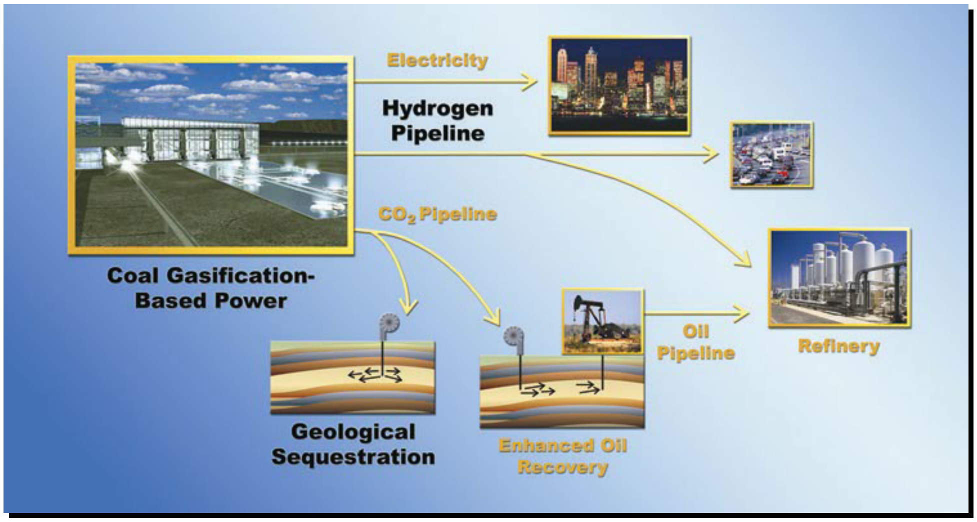
2.0 REDUCING EMISSIONS FROM ENERGY SUPPLY

2.1 LOW EMISSIONS FOSSIL-BASED POWER AND FUELS

2.1.1 ZERO-EMISSION POWER, HYDROGEN, AND OTHER VALUE-ADDED PRODUCTS

Technology Description



FutureGen Power Plant

Coproduction technology focuses on developing plants that coproduce electricity and transportation fuel from fossil or opportunity fuels with very large reductions in CO_2 emissions compared to present technologies. Two approaches may be developed. Both approaches employ synthesis gas generated from natural gas reforming or coal gasification. Carbon emissions are reduced in the near-term approach principally by improving process efficiency (e.g. warm gas cleanup, separation membranes); and in the longer term, via more advanced system components such as high-efficiency fuel cells. In both the near and long term, incorporating CO_2 collection into the process, followed by permanent sequestration will be required to achieve zero emissions.

System Concepts

- Synthesis gas is used from a variety of feedstocks including coal, petroleum coke, biomass, opportunity fuel, and natural gas. For solid feedstocks, the initial processing involves gasification followed by gas cleanup (particulate matter, sulfur, nitrogen compounds). For natural gas feed, the initial step is partial oxidation reforming. All new technologies to be developed for the long-term approach of coproduction will work equally well with solid or gas feedstocks.
- The core approach is to employ water gas shifting of syngas to maximize production of hydrogen and carbon dioxide, which allows carbon capture prior to combustion.
- Nominal carbon capture for the near-term approach (including both net power and fuel production) is 90% of feedstock carbon used for conversion. For the long-term approach, carbon capture will be more than 99%.
- Power production is via combustion turbine/steam turbine combined cycle in the near-term approach. Power production is via solid-state fuel cell combined cycle in the long-term approach.
- The near-term approach accomplishes carbon capture by absorption from shifted syngas into a physical solvent such as Selexol. Use of a physical solvent instead of chemical solvents such as amines yields energy savings in CO_2 recovery.
- The principal fuel product anticipated with the near-term approach is Fischer-Tropsch diesel fuel, a premium fuel or blending stock with ultra-low sulfur and aromatics. The principal fuel product with the long-term approach is high-purity hydrogen.
- The long-term approach will employ ceramic membranes for oxygen separation and for hydrogen separation.

Representative Technologies

- Gasifiers for solid feedstocks.
- Partial oxidation reformers for natural gas feedstock.
- Shift reactors (both approaches).
- Hydrogen-fueled combustion turbines (near-term approach).
- Steam turbines for combined cycle power generation (near-term approach).
- Fischer-Tropsch reactors and product recovery train (near-term approach).
- Physical solvent-based absorption system for CO_2 recovery (near-term approach).
- Cryogenic oxygen separation (near-term approach).
- Ion transport membranes for oxygen separation and ceramic membranes for hydrogen recovery (long-term approach).
- Solid-oxide fuel cells (long-term approach).
- CO_2 compression and drying system (both approaches).

Technology Status/Applications

- The only technology module that needs to be developed for the near-term approach is the hydrogen combustion turbine. Major turbine manufacturers (e.g., GE, Siemens-Westinghouse) have performed design studies on the modifications that would be required on existing combustion turbines. Test results indicate the modifications are technically feasible.
- Absorption of CO_2 in a physical solvent has not been practiced commercially at the large scale that will be required at a central coproduction plant (about 5,000 tpd CO_2 for a 250-MW plant). All aspects of the technology are proven, however, so scale-up should be straightforward.
- Fischer-Tropsch conversion is a commercial process used in South Africa (Arge reactors) to convert both coal- and natural-gas-derived syngas to liquid fuels and chemicals. Fischer-Tropsch conversion is also used commercially by Shell in Malaysia to convert natural gas to diesel fuel, solvents, and wax products. In the United States, liquid-phase synthesis with unshifted coal-derived syngas has been practiced at the LaPorte, Texas, pilot facility, and at the Eastman Chemical Co. Clean Coal Technology demonstration project.
- Ceramic membrane reactor development projects for both oxygen separation and hydrogen recovery are underway with industrial partners as part of the DOE Vision 21 program. The Vision 21 roadmap calls for both technologies to be ready for commercial use by 2015.
- Compression, drying, and transport of CO_2 at supercritical pressures already are practiced in recovery and use of CO_2 from underground sources for tertiary oil recovery.

Current Research, Development, and Demonstration

RD&D Goals

- Ten-year demonstration project (FutureGen) to create the world's first coal-based, zero-emissions electricity and hydrogen power plant. This project will be undertaken with international partners, and power and advanced technology providers to dramatically reduce air pollution and capture and store emissions of greenhouse gases.
- By 2010: Design a near-term coproduction plant configuration at 275-MW size ready for commercial deployment; demonstrate pilot-scale reactors using ceramic membranes for oxygen separation and hydrogen recovery; demonstrate $400/kW solid-oxide fuel cell.
- By 2020: Design a long-term coproduction plant at 275-MW or larger scale.

RD&D Challenges

- Hydrogen combustion turbine design modifications.
- CO_2 absorber demonstration at full scale.
- Plant integration issues for coproduction of Fischer-Tropsch liquids and power.
- Integration of coproduction plant with sequestration site planning.
- Ion transport membranes for oxygen separation.
- Long-term membrane reactor for hydrogen recovery.

- Low-cost solid-oxide fuel cells.
- Plant integration issues for coproduction of hydrogen and power.

RD&D Activities

- Vision 21 ion transport oxygen separation membranes
- Vision 21 hydrogen separation membranes
- Early-entrance coproduction plant designs

Recent Progress

- Air Products' liquefied petroleum methanol pilot plant at LaPorte, Texas, was scaled up to Eastman Chemicals Clean Coal Technology Project.
- Eastman Chemicals Clean Coal Technology Project successfully produced 80,000 gpd of 97% methanol, and was selected for scale-up in Global's early-entrance coproduction plant design study for the Wabash River site.

Commercialization and Deployment Activities

- Early entrance coproduction plant projects begin with a Phase I plant design for eventual commercial scale demonstration in follow-up phases.

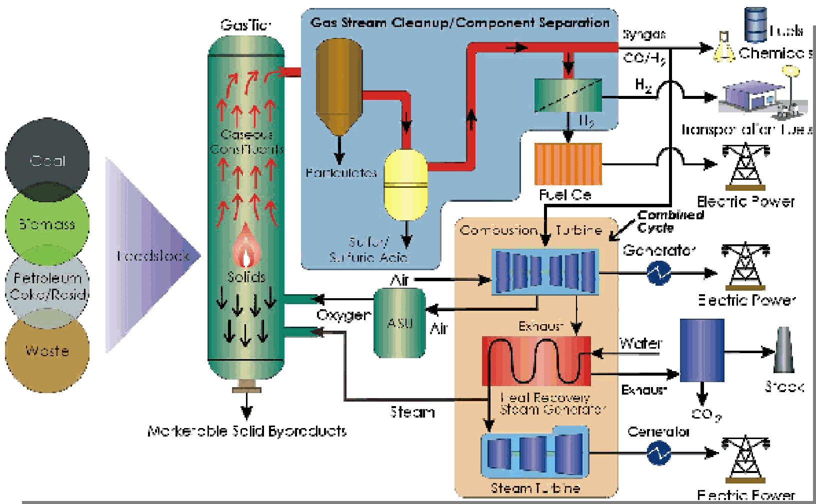
Market Context

- Coproduction plants like those described here address both the power and transportation sectors, providing energy with very large reductions in carbon intensity from large point sources of CO_2 (such as central generating stations) and could become the new world standard for providing environmentally responsible power and transportation.

2.1.2 HIGH-EFFICIENCY COAL/SOLID FEEDSTOCK

Technology Description

Advanced Gasification System



Advanced coal-fired, power-generation technologies can achieve significant reductions in CO_2 emissions while providing a reliable, efficient supply of electricity. Significant improvements in reducing CO_2 have been demonstrated via efficiency improvements and cofiring of coal and biomass. While current power plant efficiencies are about 33%, increasing efficiencies ultimately to 60% or more will reduce CO_2 emissions by more than 50% per unit of electricity. Future development of CO_2 sequestration could reduce carbon emissions to near-zero levels.

System Concepts

- Gasification technology increases the coal power-generation cycle efficiency by combining two or more energy cycles, a high-temperature gas turbine, and a steam turbine. In a typical configuration, the gasifier converts coal into a low- or medium-BTU gas, which is burned in the combustion section of the gas turbine to produce electric power. The exhaust gases from the gas turbine are cooled in the heat-recovery steam generator. The steam is routed to the steam turbine, producing additional electric power. Depending on the quality of the gas produced, the gas also may be used as the feedstock to coproduce a variety of chemicals and fuels. Steam also may be replaced with a more efficient working fluid (e.g., air or long-term binary mixtures).
- Combustion technology, including chemical looping, may use oxygen separation coupled to a coal-fired power plant featuring oxygen combustion, carbon capture, and ultra-supercritical steam-cycle operation.

Representative Technologies

- Vision 21 – the ultra-clean energy plant of the future.
- Integrated gasification combined cycle (IGCC).
- Pressurized fluidized bed combustion.
- Oxygen-combustion systems.
- Unconventional combustion (e.g., use of chemical cycling for CO_2 enrichment).

Technology Status/Applications

- Current IGCC systems based on oxygen-blown, entrained-bed gasifiers are 40%-42% efficient.
- IGCC systems with efficiencies of 40%-45% are scheduled to be available for commercial deployment by 2005.

- Efficiencies of a portfolio of IGCC technologies are expected to average 50% by 2008 and 60% by 2015.
- The cost of electricity for these technologies is expected to be 3¢–4¢/kWh (in 1997$) by 2015.
- Gasifier capital costs are expected to decrease to 90% of current costs as these technologies mature around 2010.
- Supercritical coal-fired technologies without carbon sequestration are available now with efficiencies of 42%.
- Ultra-critical steam cycles using coal-fired technologies with efficiencies in the 45% range are expected by 2010.
- Coal-fired technologies with significant potential for carbon capture are expected by 2015.
- Oxygen-fed, coal-fired power plants with near-zero CO_2 emissions are expected by 2020.

Current Research, Development, and Demonstration

R&D Goals

- Current DOE RD&D program efficiency goals range from 48%-52% in 2008 to more than 60% in 2015 at an electricity cost that is 75%-90% of current pulverized-coal-based generation.
- Emissions of criteria pollutants are targeted to be much less than one-tenth of current new source performance standards.

RD&D Challenges

- Long-term systems need to maintain relatively high temperatures between the combustion/gasification stage and the turbine stage to achieve efficiency goals.
- High-temperature materials that are stable and resistant to corrosion, erosion, and decrepitation are a primary technology development need.
- Long-term materials are needed for heat exchangers, turbine components, particulate filters, and SO_2 removal. Other challenges include the use of alternate working fluids and heat-exchange cycles, CO_2 capture methods, cycle optimization, environmental control technologies with low energy penalties, and solids handling.

RD&D Activities

- The portfolio of high-efficiency coal power systems under development through DOE is comprised of IGCC, pressurized fluidized bed combustion, and Vision 21 plants.
- DOE activities are supplemented by up to 50% cost share from the private sector.
- Current development encompasses a broad range of activities including major efforts by UNDERC, Southern Company Services, and others to develop a new class of gasifiers.
- Four IGCC clean coal demonstration projects are in various stages of completion.

Recent Progress

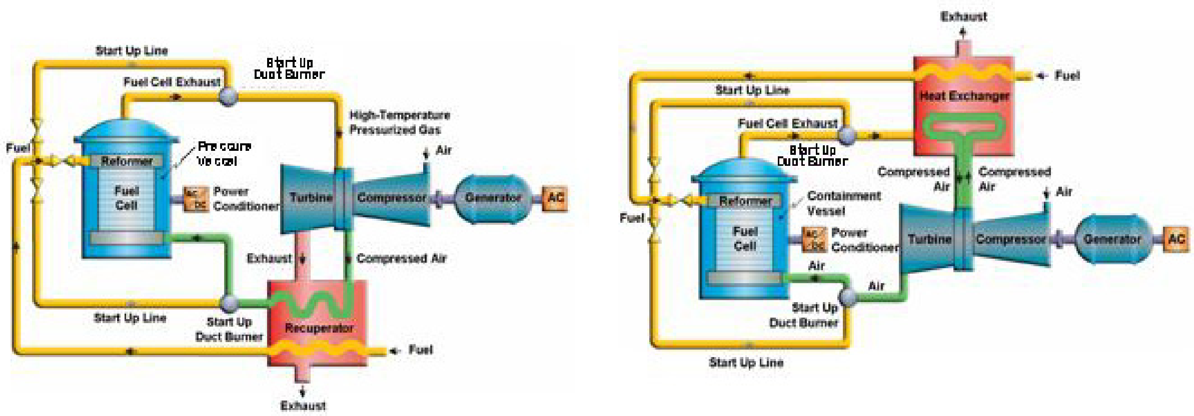
- In 1996, the IGCC Wabash River project received *Power Magazine's* Power Plant of the Year Award, "a technology to bridge the millennium…to minimize environmental impact and maximize efficiency." As one of 40 projects in the Clean Coal Technology Program, the 260-MW Wabash River repowering project increased the efficiency of an older pulverized coal unit by one-third, to 39% efficiency. Since starting in 1995, Wabash has operated more than 15,000 hours, consuming more than 1.5 Mt of coal to produce more than 4 GWh of electricity.
- In July 1996, the Polk Power Station of Tampa Electric Company began operating their gasifier. Since then, the gasifier has operated more than 25,700 hours to produce more than 7.4 GWh of electricity. During 2000, the Polk Power Stations' gasifier reached its project goal of 80% online availability. The project was presented the 1997 Power Plant Award by *Power Magazine*. Sulfur capture for the project is greater than 98%, while NO_X emissions are 75% less than a conventional pulverized coal-fired power plant.

Commercialization and Deployment Activities
• The gasification technology is under development with several recent proof-of-concept greenfield and repowering installations. Existing plants may be repowered with higher-efficiency coal technologies at or below the price of the natural gas combined-cycle plants. Where natural gas is not available (a considerable portion of the United States and a major portion of the international market) or if gas costs stay above \$4/mmbtu, high-efficiency coal plants will be the lowest-cost choice. • Internationally, where natural gas is not available, the market share for coal is expected to be much higher. **Market Context** • The market for new or repowered capacity from now until 2020 is estimated to be as much as 400 GW in the United States and more than that internationally. Domestically, the primary competition for this technology profile is expected to be natural gas combined cycle.

2.1.3 HIGH-EFFICIENCY GAS FUEL CELL/HYBRID POWER SYSTEMS

Technology Description

Fuel Cell Hybrid Cycles



Direct Fuel Cell Turbine Cycle

Indirect Fuel Cell Turbine Cycle

The ultimate goal of this technology is to develop systems that use natural gas or hydrogen (from coal, natural gas, or other sources) for highly efficient power generation. This also includes standalone applications of small to medium gas turbine systems, as well as advanced turbine systems for cogeneration application. Near-zero CO_2 emissions could be achieved with the integration of CO_2 capture.

System Concepts

- Hybrid systems that combine fuel cells and gas turbines to create a high-efficiency power module with near-zero emissions for central power or grid support applications.
- High-performance gas turbines that utilize ATS and advanced aircraft technology that use natural gas or hydrogen fuels from coal.
- Unique fuel cell turbine hybrid cycles that incorporate intercoolers, humidified air cycles, and high-pressure ratios to achieve the highest efficiency.
- High-efficiency coproduction (electricity and hydrogen) energy systems, utilizing waste heat for making hydrogen from natural gas.
- Integration in the long term of CO_2 capture technologies with all of the above systems.
- Integration of fuel cells with other heat engines (reciprocating engines, Stirling engines, etc.) to create highly efficient and clean power modules.
- Fuel cell systems, including high- and low-temperature units.

Representative Technologies

- Low- and high-temperature fuel cells.
- Optimized gas turbines with higher-pressure ratios, intercoolers, oil-less bearings.
- Smart control systems.
- Hydrogen separation membranes.
- Natural gas reforming.
- CO_2 capture.
- Membrane separators for air, hydrogen, and CO_2.
- Ultra-high temperature steam turbines.

Technology Status/Applications

- Two different fuel cell turbine hybrid power systems (300 kW) have been designed, built, and operated (Siemens Westinghouse and FuelCell Energy Inc.). Both prototype systems logged more than 3,000 hours of operation each and achieved efficiencies of approximately 52% with near-zero emissions.
- The Solid State Energy Conversion Alliance (SECA) is in the second year of an eight-year program to develop low-cost (< $400 / kW) fuel cell modules for standalone and hybrid applications.
- Micro gas turbines (available now) and certain fuel cell systems are being used now in industrial and residential (limited) applications for both power and heat.
- Proton-exchange membrane, fuel cells are available now.
- Solid oxide fuel cell technology has demonstrated long-term performance (see first bullet above). ATS spin-off technologies are being infused into mature product lines in commercial operation.
- ATS gas turbines are engaged in large-scale demonstration and poised for commercial deployment for retrofitting existing plants, for new central-station technology, and for onsite or distributed power generation.
- High-temperature fuel cells – such as molten carbonate and tubular solid oxide – are engaged in commercial-scale demonstration tests, but not yet competitively on the market.
- Fuel cells and turbines are being integrated and demonstrated at commercial scales.
- Various elements of high-performance cycles need to be developed to integrate long-term CO_2 capture, membrane separation, optimized turbines, low-cost high-performance SECA fuel cells, and ultra-high temperature steam turbines need extensive development.

Current Research, Development, and Demonstration

RD&D Goals

By 2010

- Demonstrate integrated fuel cell and turbine systems achieving efficiencies of 60% on natural gas.
- Reduce the costs of the Solid-state Energy Conversion Alliance fuel cell power system to $400/kW.

By 2020

- Demonstrate integrated fuel cell and turbine systems achieving efficiencies of 60% on coal and 75 % on natural gas.
- Integrate optimized turbine systems into zero-emission power plants.

By 2030

- Demonstrate fuel cell hybrid systems incorporating carbon capture methods that achieve near-zero CO_2 emissions to the environment.

RD&D Challenges

- Low-cost, high-performance materials.
- Compatible fuel cell and micro-gas-turbine components.
- Simpler manufacturing process and materials in fuel cells to lower costs.
- Grid interconnection.
- Reforming technology.
- Fuel cell turbine control system for steady-state and dynamic operation.
- System-specific energy-efficient environmental controls for NO_x.
- Developing new components required by long-term cycles integrating CO_2 capture.

RD&D Activities

- High-temperature fuel cell performance advancement for FCT hybrid application.
- Development of large gas turbines for FCT hybrid application.
- Systems integration and controls for hybrid FCT application.
- Hybrid systems and component demonstration.
- Low-cost fuel cell systems.
- Develop hydrogen separation, transport, and storage.
- Develop methods for CO_2 sequestration and/or capture.

- Develop high-performance materials, catalysts, and processes for reforming methane.
- Develop membranes for separation of air, hydrogen, and CO_2.

Recent Progress

- Siemens-Westinghouse has demonstrated a nominal 300 kW fuel cell turbine direct-cycle hybrid for more than 3,000 hrs. and achieved an electrical efficiency of 53%.
- FuelCell Energy, Inc., (FCE) has demonstrated a nominal 300 kW fuel cell turbine indirect cycle hybrid for more than 6,000 hrs. and achieved an electrical efficiency of 52%. FCE is currently building a fully integrated version of their 300 kW hybrid.
- Siemens-Westinghouse demonstrated a 25-kW solid oxide fuel cell for more than 13,000 hours and a 125-kW unit for more than 14,000 hours.
- The ATS program has resulted in successful design, fabrication, and testing of a gas turbine power system.
- ATS technologies developed for the ATS machine are being infused into mature gas turbine product lines yielding significant savings in fuel and emissions.
- The first commercially sold Advanced Turbine System (ATS) has been deployed by GE to Baglan Bay, U.K. The 400 MW (50 Hz.) 60% efficient unit has passed the commercial acceptance test and met power output and emissions requirements. By the end of 2003, the machine will be commercially deployed.

Commercialization and Deployment Activities

- Fuel cells are becoming viable in niche applications, and increased production rates are expected to lower capital costs.
- More than 200 fuel cell units (mostly 200-kW size) are operating worldwide.
- Currently, there are six industrial teams in the SECA program developing low-cost (< $400/kW) solid oxide fuel cell technology. The SECA program is supported by a significant core technology program to resolve technical issues. Three of the six SECA industry team have shown significant interest in developing fuel cell turbine hybrid products.
- Ballard is the primary developer of proton exchange membrane fuel cells.
- Energy losses and cost are expected to decline with system refinements.
- ATS technologies such as brush seals, coatings, and compressor technology are currently being used in a majority of the latest turbine designs.

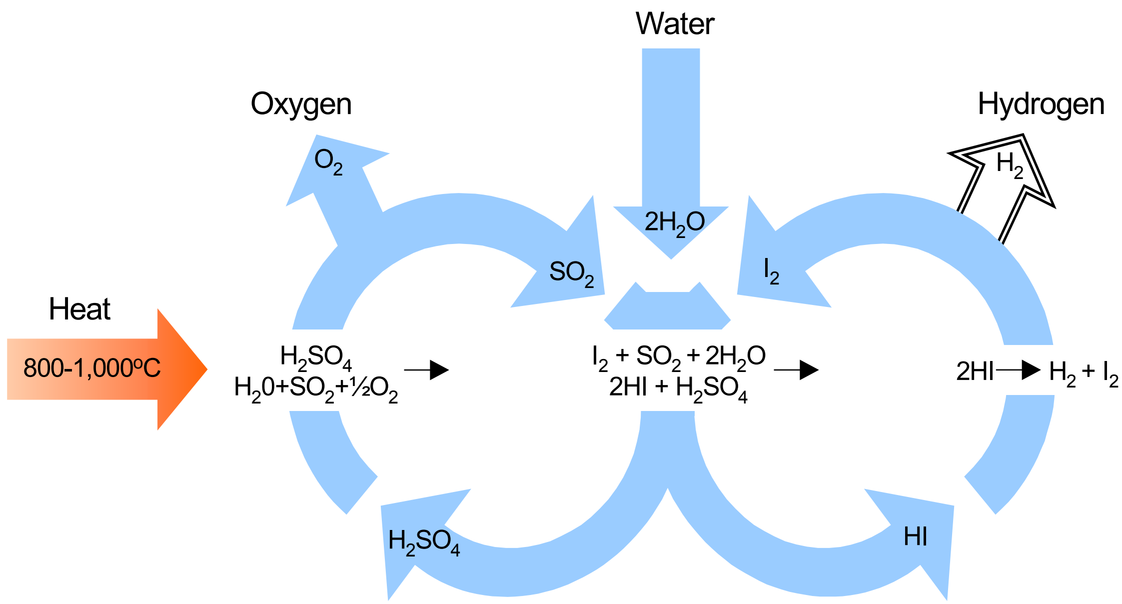
Market Context

- Fuel cell technology would provide power and space conditioning to residential, commercial, and industrial developments.
- Large domestic and international markets, greater than 200 GW both domestically and internationally. Potential applications include retrofitting existing plants and building new central-station capacity.

2.2 HYDROGEN

2.2.1 HYDROGEN PRODUCTION FROM NUCLEAR FISSION AND FUSION

Technology Description



Hydrogen is a carbon-free fuel that can be used in vehicles, homes, businesses, and power plants, and it can serve as a chemical feedstock. When hydrogen is produced from fossil fuels, CO_2 appears as a concentrated byproduct. Advanced nuclear fission and fusion systems can be used to produce hydrogen without generating CO_2. Very high-temperature, high-efficiency nuclear power plants can produce electricity to electrolyze water vapor and supply temperatures sufficiently high to drive chemical cycles for hydrogen production. Implementing these hydrogen technologies will reduce carbon emissions significantly below what is possible with nuclear-generated electricity alone.

System Concepts

- Very high-temperature, high-efficiency nuclear systems are used to drive processes for hydrogen production by electrolysis of water vapor and chemical cycles for water decomposition.
- Solid metallic alloys are used to store hydrogen without high pressurization or liquefaction.

Representative Technologies

- Very high-temperature, high-efficiency gas fission reactor.
- Lead bismuth-cooled or molten-salt-cooled fission reactor.
- Fusion reactor using gas, liquid-metal, or molten-salt cooling.

Technology Status/Applications

- Very high-temperature reactors cooled by gas or molten salts are being developed.
- Fusion technology is in development and making steady progress.
- Gas-cooled reactors operate in Japan at the temperatures of interest.
- Chemical cycles for the decomposition of water to yield hydrogen are being designed.
- Electrolysis of water vapor rather than liquid water is showing economic promise.
- Fuel-cell-powered vehicles using hydrogen are being developed and demonstrated by industry.

Current Research, Development, and Demonstration

RD&D Goals

- Economic hydrogen production without generation of CO_2.
- High-temperature, high-efficiency fission and, when available, fusion power plants to produce electricity to generate hydrogen from water economically.

- High-temperature reactors to drive chemical cycles for hydrogen production.

RD&D Challenges

- Develop reactor designs and materials that operate at temperatures high enough to achieve needed efficiencies.
- Overcome barriers to economic hydrogen generation by electrolysis.
- Develop chemical processes for water decomposition that operate efficiently and reliably.
- Demonstrate production and large-scale storage of hydrogen using a nuclear power plant.

RD&D Activities

- Preconceptual design of gas-cooled and lead-bismuth-cooled reactors and hydrogen production systems are underway as part of the Nuclear Energy Research Initiative.
- Concept development for high-temperature blanket/cooling systems is underway as part of the fusion program.

Recent Progress

- Chemical cycles for hydrogen production are being evaluated, and the conceptual design is being prepared for a gas-cooled reactor to couple to the most promising cycles.
- Japan's gas-cooled, high-temperature test reactor operates at 950°C.
- Recent analyses indicate that, because of low fuel costs, fission systems could provide cost-effective off-peak electricity for electrolysis at either onsite or offsite filling stations.

Commercialization and Deployment Activities

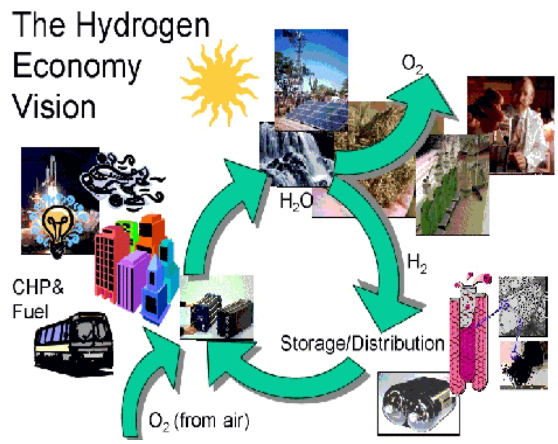
- Very high-temperature, high-efficiency test reactors are being developed in Japan.
- Fuel cell-powered vehicles will create demand for hydrogen in addition to existing demand of the process chemical industry.
- Conceptual design of high-temperature reactors has been initiated as part of the Nuclear Energy Research Initiative. High-temperature operation will make reactors competitive with other methods of electrical power generation.
- Partnering with industry to demonstrate hydrogen production using electricity during off-peak demand periods has been proposed.
- Fusion plants could be commercialized late in the second quarter of this century.

Market Context

- The potential for carbon emissions reductions using these technologies is enormous, including consideration of the GHG reduction from the significant improvements in the efficiency of electrical power generation.
- Hydrogen fuel cell vehicles will create a demand for hydrogen as a transportation fuel in addition to the demand by the process chemical industry. Petroleum industry demand for hydrogen will grow as the use of lower-quality crude oils becomes more common in refining.
- Extends the applicability of large fission energy resources and essentially unlimited fusion energy resources to the transportation sector.

2.2.2 INTEGRATED HYDROGEN ENERGY SYSTEMS

Technology Description



Like electricity, hydrogen can be produced from many sources, including fossil fuels, renewable resources, and nuclear energy. Hydrogen and electricity can be converted from one to the other using electrolyzers (electricity to hydrogen) and fuel cells (hydrogen to electricity). Hydrogen is an effective energy-storage medium, particularly for distributed generation. Implementation of hydrogen energy systems could play a major role in addressing climate challenges and national security issues through 2030 and beyond. Today, hydrogen is produced primarily from natural gas using widely known commercial thermal processes. In the future, it could be produced directly from renewable resources. In the meantime, we can adapt current technologies to produce hydrogen with significantly reduced CO_2 emissions, through carbon capture and sequestration processes, and by using renewable and nuclear electricity to produce hydrogen with no production-side CO_2 emissions. Using hydrogen in combustion devices or fuel cells results in few, if any, harmful emissions.

The vision for a hydrogen economy is based on a clean and simple cycle: separate water into hydrogen and oxygen using renewable energy such as solar. Use the hydrogen to power a fuel cell, where hydrogen and oxygen (from air) recombine to produce electrical energy, heat, and water to complete the cycle. This process produces no particulates, no carbon dioxide, and no pollution.

In the next 20-30 years, hydrogen systems used for stationary and vehicular applications could solve many of our energy and environmental security concerns. Hydrogen is likely to be affordable, safe, domestically produced, and used in all sectors of the economy and in all regions of the country.

System Concepts and Representative Technologies

- A hydrogen system is comprised of production, storage and distribution, and use. Technologies are in various stages of development across the system. Hydrogen made via electrolysis from excess nuclear or renewable energy can be used as a sustainable transportation fuel or stored to meet peak-power demand. It also can be used as a feedstock in chemical processes.
- Hydrogen produced by decarbonization of fossil fuels followed by sequestration of the carbon can enable the continued use of fossil fuels in a clean manner during the transition to the ultimate carbon-free hydrogen energy system.
- For hydrogen to become an important energy carrier – as electricity is now – an infrastructure must be developed. Although the ultimate transition to a hydrogen economy requires significant infrastructure investments, it is possible to develop the components of a hydrogen energy system in parallel with infrastructure. As hydrogen applications become more cost effective and ubiquitous, the infrastructure will also evolve. Beginning with fleets of buses and delivery vans, the transportation infrastructure will evolve to include sufficient refueling islands to enable consumers to consider hydrogen vehicles as attractive and convenient. The development of distributed power systems will begin with natural gas-reformer systems and evolve to provide hydrogen from a variety of resources (for all services), including hydrogen-to-fuel vehicles, reliable/affordable power, lighting, heating, cooling, and other services for buildings and homes.

Technology Status/Applications

- Today, hydrogen is primarily used as a chemical feedstock in the petrochemical, food, electronics, and metallurgical processing industries. Hydrogen is receiving new capital investments for transportation and power-generation applications.
- Nearly half of the worldwide production of hydrogen is via large-scale steam reforming of natural gas, a relatively low-carbon fuel/feedstock. In the United States, almost all of the hydrogen used as a chemical (i.e., for petroleum refining and upgrading, and ammonia production) is produced from natural gas. Today,

we safely use about 90 billion m^3 (3.2 trillion ft^3) of hydrogen yearly. Although comparatively little hydrogen is currently used as fuel or as an energy carrier, there are emerging trends that will drive the future consumption of hydrogen.

- The long-term goal of the DOE Hydrogen, Fuel Cell & Infrastructure Technologies (HFC&IT) Program is to make a transition to a hydrogen-based energy system in which hydrogen will join electricity as a major energy carrier. Furthermore, much of the hydrogen will be derived from domestically plentiful resources, making the hydrogen economy an important foundation for sustainable development and energy security.
- Requirements in California – especially the Los Angeles basin – are propelling the development of zero-emission vehicles, which in turn, provide incentives for the growth of fuel cell cars, trucks, and buses. Several bus fleets are currently incorporating hydrogen and fuel cell technologies into their fleets. Major car manufacturers are developing fuel cell vehicles in response to concerns about greenhouse gas and other emissions, and in response to policy drivers, especially for higher efficiencies and reduced oil consumption.
- Integrating the components of a hydrogen system in a variety of applications enables the continued development of infrastructure that is needed as we move from concept to reality. The development of the components of an integrated hydrogen system has begun:
- *Production*: Hydrogen production from conventional fossil-fuel feedstocks is commercial, and results in significant CO_2 emissions. Large-scale CO_2 sequestration options have not been proven and require R&D. Current commercial electrolyzers are 70%-80% efficient, but the cost of hydrogen is strongly dependent on the cost of the electricity used to split water into hydrogen and oxygen. Production processes using wastes and biomass are under development, with a number of engineering scale-up projects underway. Longer-term, direct hydrogen production processes (photoconversion) are largely in the research stage, with significant progress being made toward development of cost-effective, efficient, clean systems.
- *Storage and Distribution*: Liquid and compressed gas tanks are available and have been demonstrated in a small number of bus and automobile demonstration projects. Lightweight, fiber-wrapped tanks have been developed and tested for higher-pressure hydrogen storage. Experimental metal hydride tanks have been used in automobile demonstrations. Alternative solid-state storage systems using alanates and carbon nanotubes are under development. Current commercial practices for the distribution and delivery of hydrogen – including truck, rail, and barge delivery of liquid or compressed gas – will provide the most cost-effective hydrogen until demand increases and additional infrastructure is developed.
- *Use*: Small demonstrations by domestic and foreign auto and bus companies have been undertaken. Small-scale power systems using fuel cells are being beta-tested. Small fuel cells for battery replacement applications have been developed.

Current Research, Development, and Demonstration

RD&D Goals

- By 2005: (1) develop auxiliary equipment (including sensors) that enable the use of hydrogen as a fuel and energy carrier; (2) investigate material compatibility and durability issues, as well as evaluate network capacity related to distribution of hydrogen; (3) install refuelers in key locations; and (4) adopt codes and standards for hydrogen systems.
- By 2010: (1) define a cost-effective hydrogen delivery infrastructure; (2) verify technologies that reduce the delivery cost of hydrogen for distances less than 200 miles to less than \$.70/kg; and (2) verify technologies that reduce the moving and handling cost of hydrogen within the refueling station or power generation facility to less than \$.60/kg.
- By 2015: (1) verify technologies to deliver hydrogen from the point of production to the point of use for a cost of less than \$1/kg.

RD&D Challenges

- Codes and standards must be developed and implemented; appropriate supporting research and modeling are needed to validate system designs and operating procedures.
- Enabling technologies such as sensors need to be developed and commercialized.
- Infrastructure can be developed step-wise for the near-term, but eventually must be widespread and cost-effective. Thoughtful development schemes are needed to maximize the value of the investment.

RD&D Activities

- DOE's HFC&IT Program is carried out by national laboratories, universities, and the private sector, including CRADA collaborations between industry and the labs, and cost-shared industry-led efforts.
- The overall strategy of the HFC&IT Program is to conduct a comprehensive and balanced program that includes mid- and long-term research and development of hydrogen production, storage, and utilization technologies; integrated systems and technology validation using close collaboration with industry that develops, demonstrates, and deploys critical technologies emerging from research and development; and an analysis element that helps determine the performance and cost targets that technologies must meet to achieve goals of the HFC&IT Program, as well as specific project objectives determined by peer review.

Recent Progress

- A complex integrated demonstration project is operated by SunLine Transit (Thousand Palms, California). The project includes both fossil- and renewable-hydrogen production, compressed gas storage and hydrogen use for transportation (public transit), and stationary power (educational displays). The refueling facility is open to the public and provides pressurized and liquid hydrogen, hydrogen/natural gas blends, and natural gas. The transit fleet includes buses running on hydrogen/natural gas blends and an Xcellsis fuel cell bus.
- A number of hydrogen/fuel cell personal vehicles (modified golf carts) have successfully been operated by Palm Desert (California), in conjunction with the Schatz Energy Research Center/Humboldt State University and with support from the DOE HFC&IT Program.
- Hydrogen refueling equipment (liquid delivered to the facility) – to provide hydrogen to the small fleet of hydrogen fuel cell vehicles that are currently being tested in California – has been installed by the California Fuel Cell Partnership (Sacramento, California).

Commercialization and Deployment Activities

- Major industrial companies are pursuing R&D in fuel cells and hydrogen reformation technologies with a mid-term (5-10 years) timeframe to deploy these technologies for both stationary and vehicular applications. These companies include ExxonMobil, Shell, Texaco, BP, General Motors, Ford, Daimler-Chrysler, Toyota, Honda, United Technology Corporation Fuel Cells, Ballard, Air Products, and Praxair.
- To address the key barrier of perceived safety, the DOE initiated a successful effort to have the International Code Council (ICC) form a special committee to develop provisions specific to hydrogen for incorporation into its model building, fire, and fuel gas codes, which the ICC will publish for adoption by local jurisdictions throughout the United States. The ICC model codes will incorporate standards for hydrogen components and equipment being developed by leading organizations, such as the Society of Automotive Engineers and the International Standards Organization.
- The DOE completed a technology vision and roadmapping effort with industry to develop a framework for public-private partnerships to develop and deploy a national hydrogen infrastructure. The report was unveiled on November 12, 2002, by the Energy Secretary.

2.2.3 HYDROGEN PRODUCTION

Technology Description

Similar to electricity, hydrogen can be produced from many sources, including fossil fuels, renewable resources, and nuclear energy. Today, hydrogen is produced primarily from natural gas using widely known commercial thermal processes. In the future, it could be produced directly from renewable resources. In the meantime, we can adapt current technologies to produce hydrogen with significantly reduced CO_2 emissions, through carbon capture and sequestration – and by using renewable and nuclear electricity to produce hydrogen with no production-side CO_2 emissions.

System Concepts and Representative Technologies

- Feedstock flexibility is an essential and unique feature of hydrogen systems. With only minor modifications to existing and developing technologies, hydrogen can be produced efficiently and cleanly from nearly any resource.
- Hydrogen made via electrolysis from excess nuclear or renewable power can be used as a sustainable transportation fuel or stored to meet peak-power demand. Hydrogen as a storage medium enables intermittent renewable power systems to provide reliable power, even when the wind is not blowing or the sun is not shining.
- Hydrogen produced by decarbonization of fossil fuels (followed by sequestration of the carbon) can enable the continued use of fossil fuels in a clean manner during the transition to the ultimate carbon-free hydrogen energy system.
- Biomass can be used to produce hydrogen and other value-added coproducts such as activated carbon, fuel additives, and adhesives, when it is thermally treated under relatively mild conditions. This is part of the biorefinery concept, wherein chemicals, fuels, and materials are produced from biomass resources in an integrated process.
- Hydrogen separation and purification process improvements offer cost reduction and efficiency improvement opportunities for current fossil-based systems.
- An ultimate hydrogen economy vision features hydrogen production from sunlight and water via photoconversion. Several processes, including semiconductor and biological, are under development to provide clean hydrogen for the hydrogen economy.

Technology Status/Applications

- Nearly half of the worldwide production of hydrogen is via large-scale steam reforming of natural gas (a relatively low-carbon fuel/feedstock). In the United States, almost all of the hydrogen used as a chemical (i.e., for petroleum refining and upgrading, ammonia production) is produced from natural gas. Today, we safely use about 90 billion m^3 (3.2 trillion ft^3) of hydrogen yearly. Although comparatively little hydrogen is currently used as fuel or as an energy carrier, there are emerging trends that will drive the future consumption of hydrogen.
- Hydrogen production from conventional fossil-fuel feedstocks is commercial (on a large scale), but results in significant CO_2 emissions.
- Current commercial electrolyzers are 70%-80% efficient, but the cost of hydrogen is strongly dependent on the cost of electricity.
- Small-scale reformers are under development for use as on-site hydrogen generators at refueling sites or in power parks.
- Biomass (dedicated feedstocks, agricultural and forest residues, and municipal waste) is being evaluated and tested as feeds for multiproduct biorefineries.
- Longer-term, direct hydrogen production processes – such as nuclear-based thermochemical cycles and high-temperature water-splitting, as well as photoconversion (photobiological, photoelectrochemical, and photochemical) water-splitting – are largely in the research stage. Significant progress is being made toward development of cost-effective, efficient, clean systems.

Current Research, Development, and Demonstration

RD&D Goals

Hydrogen production by photovoltaic hydrolysis.

- By 2005: (1) demonstrate small-scale steam methane reformers with a projected cost of $3.00/kg hydrogen at the pump; (2) develop alternative reactors, including autothermal, ceramic membrane, and microchannel reactors; (3) verify renewable integrated hydrogen production with water electrolysis at a projected capital cost of $300/kW for 236 kg/day capacity, delivered at 5,000 psi.
- By 2010: (1) demonstrate, at the pilot-scale, membrane separation and reactive/membrane separation technology for cost-effective hydrogen production from coal; (2) demonstrate hydrogen production from natural gas or liquid fuels that project to a cost equivalent to gasoline.
- By 2012: complete design of commercial-scale, nuclear-based hydrogen production system.
- By 2015: (1) demonstrate, at lab-scale, nuclear/thermochemical cycle hydrogen production; (2) demonstrate, at lab-scale, a photoelectrochemical water-splitting system; (3) demonstrate, at lab-scale, a biological system for water-splitting; (4) demonstrate a zero-emission coal plant for power and hydrogen production, with plant-gate hydrogen costs of $.79/kg.

RD&D Challenges

- Efficient and cost-effective small-scale reformers have not been demonstrated. New design concepts, including alternative catalysts, need to be fully developed and tested. Start-up and system cycling need to be addressed.
- Alternative reactor designs (autothermal, ceramic membrane, and microchannel) show promise for fossil-based production, but need to be tested and optimized before they can be considered for commercial development and operation.
- Electrolyzers operating at higher temperatures could provide more cost-effective hydrogen (higher efficiency/reduced electricity demand). Integration with intermittent renewable resources requires development of control strategies and/or design modifications.
- Engineering challenges need to be addressed in the scale-up and operation of the integrated biorefinery concept at an industrial site, including process control during start-up, shutdown, and upset conditions; process optimization; and integration with existing facilities.
- Hydrogen production via chemical cycles using high-temperature waste heat from nuclear power plants will need to be developed and then demonstrated in alternative facilities before it can be considered for integration near nuclear facilities.
- Photoconversion R&D efforts – including photoelectrochemical, photobiological, and photochemical processes – are presently at the basic research stage. In order to continue advancing these technologies to the applied and engineering stages, research must be supported at universities and national labs.

RD&D Activities

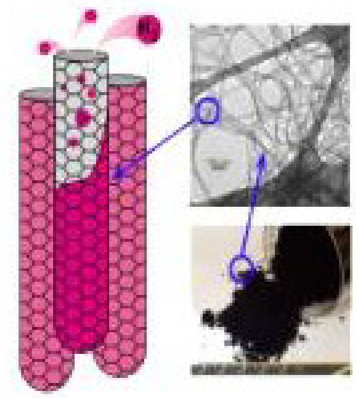
- DOE's HFC&IT Program is carried out by national laboratories, universities, and the private sector, including CRADA collaborations between industry and the national labs, and cost-shared industry-led efforts.
- The overall strategy of the HFC&IT Program is to conduct a comprehensive and balanced program that includes mid- and long-term research and development of hydrogen production, storage, and utilization technologies; integrated systems and technology validation with close industry collaboration that develops, demonstrates, and deploys critical technologies emerging from research and development; and an analysis element that helps to determine the performance and cost targets that technologies must meet to achieve the overall goals of the HFC&IT Program, as well as the specific project objectives determined by peer review.

Recent Progress
• A cooperative project between industry and an Arizona utility demonstrated a fully functional integrated renewable hydrogen utility system for the generation of hydrogen using concentrated solar power. • Intermittent renewable resources (wind and solar) were used to produce hydrogen via electrolysis in a renewable energy fuel cell system in Reno, Nevada. • An industry-led project has developed fueling appliances for small fleets and for home refueling of passenger vehicles. Both types of refueling appliance deliver gaseous hydrogen at up to 5,000 psi to the vehicle. • An autothermal reformer was installed and operated at a transit agency in California to generate hydrogen for buses and other vehicles. Also at this facility, a PV-electrolysis system is operated to provide renewable hydrogen to the same vehicles.
Commercialization and Deployment Activities
• In an industry-university-national lab partnership, agricultural residues are being used to produce hydrogen and valuable coproducts. Peanut shells represent both a waste-disposal issue and a valuable resource. Pyrolysis of the densified shells results in a valuable vapor stream that can be used to produce chemicals and hydrogen, and in a solid stream that is used to make activated carbon. This concept is currently being tested in a pilot plant, in preparation for operation at an industrial site in Georgia. • An industry-led project is installing a small-scale steam methane reformer to provide hydrogen for vehicles in the Las Vegas, Nevada, area.

2.2.4 HYDROGEN STORAGE AND DISTRIBUTION

Technology Description

Unlike electricity, hydrogen can be stored for long periods of time and distributed over long distances without significant losses. Today, hydrogen is stored as a liquid or compressed gas, and distributed by truck, rail, and (to a limited extent) pipeline. In the future, it could be stored in chemical and metal hydrides and carbon nanostructure materials, and distributed via a vast network of pipelines. In the meantime, current technologies can be adapted to store and distribute hydrogen to the emerging transportation and stationary markets for hydrogen.



Carbon nanotube structure and micrographs.

System Concepts and Representative Technologies

- There are five hydrogen storage approaches under development at the present time: high-pressure composite tanks; low-temperature hydrogen storage; pressurized cryotanks; novel carbon structures as storage media; and reversible catalyst-assisted chemical and metal hydrides.
- Solid-state storage may offer increased safety for onboard storage of hydrogen, since tank punctures or ruptures would not result in large energy releases. These systems also require less volume than pressurized or liquid systems. Stationary applications also would benefit from the successful development of these systems.
- Distribution concepts include evaluation of existing natural gas pipelines for material compatibility, utilization of the existing delivery infrastructure to provide hydrogen to emerging markets, and improved auxiliary equipment (compressors, liquefaction equipment, valves, and gauges).

High-pressure, all-composite gaseous hydrogen storage cylinders encourage commercialization of hydrogen gas-powered vehicles.

Technology Status/Applications

- Hydrogen is stored as a liquid at 20 K in insulated dewars or as a compressed gas. Metal hydrides are used in limited stationary applications where weight is not a critical factor and where waste heat is available at the appropriate temperature for hydrogen release.
- Current R&D efforts are focused on improving such factors as weight, volume, cost, and safety.
- Particularly notable are recent advances in storage energy densities, primarily focused on mobile applications. The composite tank development is a prime example of a successful technology partnership among the national labs, DOE, and industry.
- Industrial investment in chemical hydride development has recently been initiated.
- Continued improvements are still required to meet perceived customer demands in vehicular applications, in particular with respect to convenience, safety, and cost.

Current Research, Development, and Demonstration

RD&D Goals

- By 2005: develop storage system with 4.5 wt%, 1,200 watt-hrs/liter energy density, at a cost of $6/kWh of stored energy.

- By 2010: demonstrate storage system with 6 wt%, 1,500 watt-hrs/liter energy density, a range >300 miles, at a cost of $4/kWh of stored energy.

RD&D Challenges

- Fundamental understanding of chemical and metal hydrides and carbon nanotubes as hydrogen storage media is needed to enable the efficient and timely development of storage systems that are inherently safe and more efficient and convenient than current systems.
- Onboard hydrogen storage for transportation applications requires increased storage density, so that the volume of storage on a vehicle can be reduced while providing range equal to that of a conventionally fueled vehicle, without compromising vehicle weight and performance.
- Development of improved low-permeability membrane liners for pressurized storage systems is needed to further improve storage volumes and reduce container weight.
- Research and development of advanced solid-state hydrogen storage systems – including chemical hydrides, metal hydrides such as alanates, and carbon materials – needs to be broadened, with deployment of the resultant systems in prototype vehicles and/or at user sites.
- Production processes for solid-state materials need to be developed and scaled up with industry.
- Compression energy requirements at high storage pressures are significant. Improved hydrogen compressors are needed.
- Improved liquefaction equipment that uses less energy to liquefy hydrogen compared to conventional processes (where 30%-35% of the energy contained in the hydrogen is required) could provide additional storage options for stationary applications.

RD&D Activities

- DOE's HFC&IT Program is carried out by national laboratories, universities, and the private sector, including CRADA collaborations between industry and the labs, and cost-shared industry-led efforts.
- The overall strategy of the HFC&IT Program is to conduct a comprehensive and balanced program that includes mid- and long-term research and development of hydrogen production, storage, and utilization technologies; integrated systems and technology validation with close industry collaboration that develops, demonstrates, and deploys critical technologies emerging from research and development; and an analysis element that helps to determine the performance and cost targets that technologies must meet to achieve the overall goals of the HFC&IT Program, as well as the specific project objectives determined by peer review.

Recent Progress

- High-pressure, composite storage tanks have been developed through the combined efforts of industry, national labs, and universities. These tanks have been tested and certified, and are being used in prototype hydrogen fuel cell vehicles.
- Hydride storage systems have been developed for use in mining vehicles, where the added weight of these storage systems is a benefit (improved traction).
- Sodium borohydride ($NaBH_4$) is being considered for use in fuel cell vehicles as a storage/delivery system for hydrogen.

Commercialization and Deployment Activities

- A novel thermal hydrogen compressor is being developed in an industry-led project. This compressor operates in conjunction with advanced hydrogen production technologies and improves the efficiency and economics of the compression and hydrogen utilization process. The thermal compressor is an absorption-based system that uses the properties of reversible metal hydride alloys to silently and cleanly compress hydrogen; hydrogen is absorbed into an alloy bed at ambient temperature; and, subsequently, is released at elevated pressure when the bed is heated with hot water. Compression energy can be supplied by waste heat or solar hot water.
- An industry-led project is developing metal-hydride storage containers for use on scooters, wheelchairs, and other personal mobility products.

2.2.5 HYDROGEN USE

Technology Description

In the next 20-30 years, solutions for energy and environmental security may be based on the development of hydrogen systems for stationary power and vehicle applications. Hydrogen is likely to be affordable, safe, domestically produced, and used in all sectors of the economy and in all regions of the country.

Fuel cells are an important enabling technology for the Hydrogen Future. Using hydrogen to power a fuel cell – where hydrogen and oxygen (from air) combine to produce electrical energy, heat, and water – produces no particulates, no carbon dioxide, and no pollution. Even in an early transition strategy using fossil fuels, fuel cells can have near-term environmental benefits through higher-efficiency conversion of chemical energy to electrical energy. The high efficiency of the fuel cell compared to conventional conversion devices results in lower emissions of greenhouse gases and overall reduced fossil fuel use. In addition to fuel cells, turbines and internal combustion engines are being developed or modified to run on hydrogen or hydrogen-blended fuels, with reduced emissions. High-value products, such as uninterruptible power supplies and portable power generators, are likely early-entry markets for hydrogen systems. In the longer-term, hydrogen also is expected to be used in airplanes and in ships to provide carbon-free transportation.

The demand for distributed generation that provides reliable, high-quality efficient power is spurring the development of fuel cells that will provide electricity both to the grid and to on-site consumers. These distributed power systems can achieve even higher efficiencies when waste heat is used on-site for space heating or hot-water systems.

System Concepts and Representative Technologies

- Transportation sector: internal combustion engines or fuel cells to power vehicles with electric power trains, with long-term use as an aviation fuel and in marine applications.
- Industrial sector: ammonia production, reductant in metal production, hydrotreating of crude oils, hydrogenation of oils in the food industry, reducing agent in electronics industry, etc.
- Power sector: fuel cells, gas turbines, generators for distributed power generation.
- Buildings sector: combined heat, power, and fuel applications using fuel cells.

Technology Status/Applications

- The emphasis of current RD&D efforts for transportation applications is on the polymer electrolyte membrane (PEM) fuel cell, which offers simplicity, high-power density, and projected system durability. The low operating temperature of PEM fuel cells allows rapid start-up and makes them attractive for transportation applications, where many start-stop cycles are expected. Industrial participation in PEM system development is booming, with all major automobile manufactures and several fuel cell-specific companies investing in development and deployment activities.
- Emission-reduction requirements are propelling the development of zero-emission vehicles – which, in turn, provide incentives for the growth of hydrogen-powered fuel cell cars, trucks, and buses. Several transit bus fleets are currently incorporating hydrogen and fuel cell technologies into their fleets via limited demonstration projects. Major car manufacturers are developing fuel cell vehicles in response to growing concerns about greenhouse gas and other emissions; and in response to policy drivers, especially for higher efficiencies, significantly lower tailpipe emissions, and reduced oil consumption.
- Current R&D on hydrogen-fueled internal combustion engines (ICEs) is reasonably mature. Several auto manufacturers have developed hydrogen ICEs – Daimler (1975), BMW (1990s), Mazda (1991), Ford

(1999); BMW is currently touring with its 740-series, hydrogen-fueled sedan; and hydrogen-natural gas blends are used for light-duty trucks and transit buses.

- The electrical generator is based on developed internal combustion reciprocating engine technology. It is able to operate on many hydrogen-containing fuels. The efficiency and emissions are comparable to fuel cells (50% fuel to electricity conversion efficiency and essentially zero NO_x). This electrical generator is applicable to stationary power and hybrid vehicles. It allows some markets to use hydrogen economically.

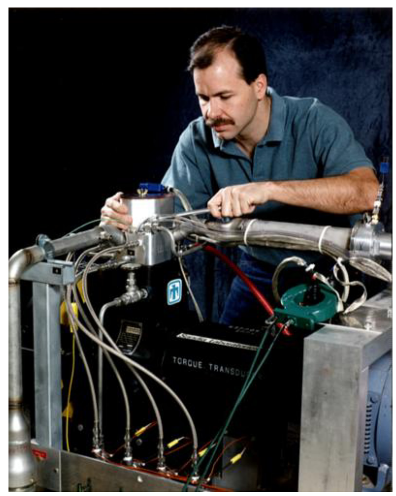
Current Research, Development, and Demonstration

RD&D Goals

- By 2005: (1) demonstrate PEM fuel cells and hydrogen ICEs in a small number of vehicles; (2) demonstrate uninterruptible power supplies and hydrogen applications in power parks.
- By 2010: (1) demonstrate a solid oxide fuel cell with projected capital costs of $400/kW for coal-fueled fuel cell/turbine hybrids; (2) demonstrate hydrogen-fueled PEM fuel cells in automobile application with a 60% peak efficiency, 220 W/liter energy density, 325 W/kg specific power, at a projected cost of $45/kW; (3) demonstrate hydrogen PEM fuel cell vehicles with 2,000 hours of durability at multiple sites.
- By 2015: (1) demonstrate PEM fuel cells for automotive applications at a projected cost of $30/kW; (2) demonstrate a fuel cell/turbine hybrid operating on coal with a system efficiency of 70% with carbon sequestration and capital costs of $400/kW.

RD&D Challenges

- Efforts to reduce costs and improve reliability of high-temperature and reversible fuel cells for stationary applications are needed.
- New high-temperature, anhydrous fast-proton-conducting membranes for use in new high-performance fuel cells need to be further developed. These new nanoengineered glass-ceramic proton conducting membranes are expected to yield high proton conductivities between 100° and 300°C, excellent thermal stability up to 300°C, superior electrochemical and chemical stability, and zero fuel crossover diffusion.
- Increased hydrogen content in natural gas-hydrogen blends needs to be tested in gas turbines to establish hydrogen's impact on reducing NO_x emissions. Development of a detailed understanding of the effect of hydrogen addition to gas turbines (kinetics, fluid dynamics, flame structure) is needed, working with industrial partners to implement hydrogen-natural gas turbines as distributed and centralized generation devices.



RD&D Activities

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Recent Progress

- Air-Breather fuel cells were developed that are exceedingly simple and most effective for small power demands such as pocket-sized portable devices.
- A gasoline ICE scooter was converted to run on hydrogen, with an onboard metal hydride storage system. Because the foreign market for scooters is very large (compared to the U.S. market), this represents a large export opportunity.

• A retrofit strategy for light- and medium-duty vehicles was developed and implemented to convert them to operate on mixtures of hydrogen and natural gas. The vehicles achieve equal vehicle range and reduced exhaust emissions, and are more powerful than the same vehicle operating on natural gas alone.
Commercialization and Deployment Activities
• Major industrial companies are pursuing R&D in fuel cells with a mid-term (5-10 years) timeframe for deployment of these technologies for both stationary and vehicular applications. These companies include General Motors, Ford, Daimler-Chrysler, Toyota, Honda, United Technology Corporation Fuel Cells, Xcellsis, and Ballard. • Several auto manufacturers have developed hydrogen ICEs – Daimler (1975), BMW (1990s), Mazda (1991), Ford (1999); BMW is currently touring with its 740-series hydrogen-fueled sedan; and hydrogen-natural gas blends are used for light-duty trucks and transit buses. • The program has launched a technology vision and roadmapping effort with industry to develop a framework for public-private partnerships to develop and deploy a national hydrogen infrastructure.

2.2.6 HYDROGEN INFRASTRUCTURE SAFETY RESEARCH AND DEVELOPMENT

Technology Description

Like other commodities used as fuels in today's energy and transportation systems, hydrogen is classified as a hazardous material. Direct transport and storage of hydrogen can be achieved via pipelines, compressed gas storage vessels/cylinders, cryogenic vessels, as a hydride, or contained in a nanostructured material. Other commodities, including natural gas and methanol, also can be used as hydrogen carriers that are later reformed. Extensive hydrogen infrastructure is already in place to meet the transport needs of the petrochemical, electronics, and food industries. However, in order to meet the potential future demands for hydrogen and expand its use as a fuel, additional infrastructure and advanced storage and transport methods and technologies will need to be developed and safely, securely, and reliably integrated into the existing transportation and energy infrastructures of the United States.

System Concepts and Representative Technologies

- There are currently three primary methods of hydrogen transport and storage: pipeline, vehicular commodity transport via tube-trailer/pressure vessels and cryogenic vessels, and stationary/fixed storage and fueling infrastructure.
- Within the United States, each of the three primary methods of hydrogen transport and storage is governed by a different set of regulations established by: The U.S. Department of Transportation (DOT)/Research and Special Programs Administration (RSPA) Office of Pipeline Safety, DOT/RSPA Office of Hazardous Materials Safety, and local and state fire marshals.
- The current system for transporting natural gas and hydrogen provides a reasonable foundation and model for expanding the hydrogen infrastructure. However, the current paradigm, with the exception of motor fuels and natural gas, is for hazardous materials (HAZMAT) transport to divert or restrict the transport of these materials into urban areas and through tunnels and other vulnerable transportation infrastructure.
- Current technologies include: small diameter hydrogen pipelines; DOT-approved pressure vessels and cylinders; DOT-approved cryogenic vessels; and, for stationary applications, pressure vessels complying with the American Society of Mechanical Engineers (ASME) boiler and pressure vessel code.
- New technologies developed or being proposed include very high-pressure (13,000-15,000 psi), all-composite pressure vessels meeting both DOT and ASME requirements; advanced pipeline materials that reduce and/or catalyze permeated or leaked hydrogen; hydrides; below-ground cryogenic vessels; and nanostructured materials.
- These new technologies may be additions to or replace current transportation infrastructure, or may be integrated into the existing infrastructure.

Technology Status/Applications

- Hydrogen has been transported and stored within the United States safely, securely, and reliably, for several decades using the current conventional (under 4,500 psi) technologies.
- New technologies to increase the efficiency and reduce the cost of hydrogen transport, such as advanced carbon composite cylinders and storage, are being adapted. New technologies are being reviewed and evaluated within the framework of the appropriate and necessary Federal regulations and other codes and standards. To date, many of the technologies have not met the burden of proof to demonstrate that they can meet the necessary safety requirements for transporting hydrogen in commerce.
- Other technologies, such as carbon nanotubes and advanced pipeline materials, are still in an early research and development (R&D) phase and are not ready for commercialization.
- The DOT/RSPA Office of Hazardous Materials Safety is currently reviewing applications for exemption for several technologies, including hydrides and high-pressure composite cylinder mobile fuelers, and is working with industry and the Department of Energy (DOE) to help guide safe and successful development and deployment of these technologies.

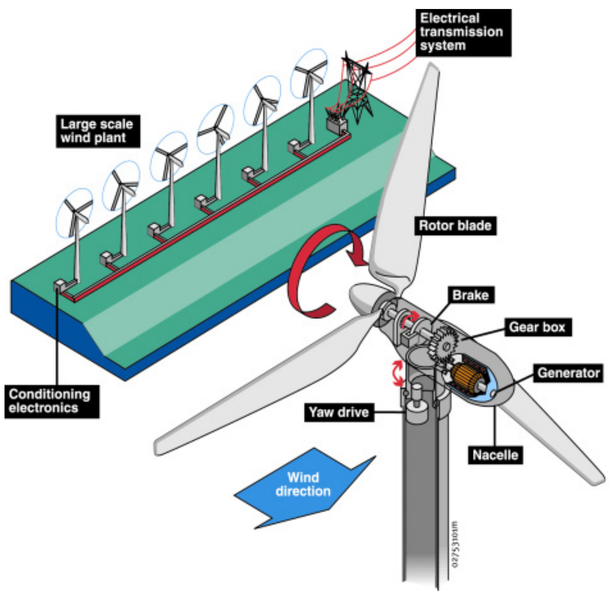
Current Research, Development, and Demonstration
RD&D Goals • Work within the Federal government and with industry to develop, test, and approve new storage and monitoring technologies. • Continue to use the exemption and regulatory development process to keep pace with the emerging technologies and applications. • Conduct a thorough and comprehensive transportation and storage infrastructure assessment to address capacity, safety, security, reliability, operations, and environmental compliance evaluating all conceived scenarios for near-term and long-term development and implementation of hydrogen infrastructure. • Conduct risk analysis for each technology and application. • Collect data on the safety, security, reliability, and operation of new technologies and systems to guide regulatory development and future deployment. • Develop a future system that offers improved safety, security, reliability, and functionality vs. the current transportation and storage systems. **RD&D Challenges** • Gain a fundamental understanding of fatigue and failure modes of advanced composites and other storage media. • Establish effective monitoring, inspection, and recertification technologies and procedures for hydrogen transport and storage. • Adapt aging infrastructure to accommodate new demands. • Educate and train operators, regulators, and users effectively. **RD&D Activities** • The Operating Administrations of DOT, specifically RSPA and the National Highway Traffic Safety Administration (NHTSA), are actively engaged in domestic and international consensus codes and standards development. • DOT staff are supporting DOE R&D activities and committees, and the activities and committees of the various consensus codes- and standards-setting organizations. • DOT staff continues to work with the National Association of State Fire Marshals to educate and train personnel and to promote safe handling and storage practices.
Recent Progress
• DOT/RSPA Office of Hazardous Materials Safety has recently approved an exemption for hydride storage of hydrogen. • In conjunction with DOE, progress is being made in the development and revision of consensus codes and standards.

2.3 RENEWABLE ENERGY AND FUELS

2.3.1 WIND ENERGY

Technology Description

Wind turbine technology converts the kinetic energy in wind to electricity. Grid-connected wind power reduces greenhouse gas emissions by displacing the need for natural gas- and coal-fired generation. Village and off-grid applications are important for displacing diesel generation and for improving quality of life, especially in developing countries.



System Concepts

- Most modern wind turbines operate using aerodynamic lift generated by airfoil-type blades, yielding much higher efficiency than traditional windmills that relied on wind "pushing" the blades. Lifting forces spin the blades, driving a generator that produces electric power in proportion to wind speed. Turbines either rotate at constant speed and directly link to the grid, or at variable speed for better performance, using a power electronics system for grid connection. Utility-scale turbines for wind plants range in size up to several megawatts, and smaller turbines (under 100 kilowatts) serve a range of distributed, remote, and standalone power applications.

Representative Technologies

- Two machine configurations are commonly used today. Three-bladed wind turbines are operated "upwind" of the tower, with the blades facing into the wind. The other common wind turbine type is the two-bladed, downwind turbine. To improve the cost-effectiveness of wind turbines, technology advances are being made for rotors and controls, drive trains, towers, manufacturing methods, and site-tailored designs.

Technology Status/Applications

- Thirty-seven states have land area with good winds (13 mph annual average at 10 m height, wind Class 4, or better). By the end of 2003, 19 states are expected to have more than 20 megawatts (MW) in operation, and wind energy installations across the United States are expected to approach 6,000 MW.
- Current performance is characterized by levelized costs of 4-6¢/kWh (depending on resource quality and financing terms), capacity factors of 30-40%, availability of 95-98%, total installed costs of $800-$1,000/kW, and efficiencies of 65-75% of theoretical (Betz limit) maximum.

Current Research, Development, and Demonstration

RD&D Goals

- Wind-farm cost/performance varies by wind resource class, ownership type, and time. Current costs range from 4¢-6¢/kWh.
- By 2004: 3¢/kWh at sites with annual average wind speeds of 16 mph (wind Class 6).
- By 2012: 3¢/kWh at sites with average wind speeds of 13 mph (wind Class 4).

RD&D Challenges

- Developing wind technology that will be economically competitive at low (13 mph) wind-speed sites requires optimizing increasingly large turbine designs for 30-year life in a fatigue-driven environment with minimal or no component replacements, requiring improved knowledge of wind inflow, aerodynamics, structural dynamics and materials, and optimal control of turbines and wind farms.
- Developing information and strategies to facilitate and optimize integration of wind power into electric grid systems.

- Develop offshore wind technology to take advantage of the immense wind resources in shallow and deep waters of U.S. coastal areas and the Great Lakes near large energy markets.
- Conduct analysis and R&D to explore the role of wind power in the production of hydrogen, in both large-scale and distributed systems.

RD&D Activities

- Core and university research: wind characteristics and forecasting, aerodynamics, structural dynamics and fatigue, and control systems for turbines and wind farms.
- Turbine research: cost-shared design and testing of next-generation utility-grade technology for low wind-speed sites, performance verification of new prototypes, development of advanced small turbines for distributed power applications, and component and system testing at the National Wind Technology Center (NWTC).
- Cooperative research and testing: collection of wind turbine-performance data, power-systems integration, resource assessment, industry technical support, participation in international standards development, wind turbine-certification assistance, and regionally targeted outreach.

Recent Progress

- In 1989, the wind program set a goal of 5¢/kWh by 1995 and 4¢/kWh by 2000 for sites with average wind speeds of 16 mph. The program and the wind industry met the goals as part of dramatic cost reductions from 25¢-50¢/kWh in the early 1980s to 4¢-6¢/kWh today.
- Wind power is the world's fastest-growing energy source. The worldwide wind market continues to grow at an annual rate above 30% with new markets opening in many developing countries. During 2002, more than 7,000 MW of new capacity was added to the electricity grid in the world.
- Domestic public interest in environmentally responsible electric generation technology is reflected by new state energy policies and in the success of "green marketing" of wind power throughout the country. U.S. wind energy installations have grown at an average rate of 24.5% during the past five years.
- The National Wind Technology Center (operated by the National Renewable Energy Laboratory in Golden, Colorado) is recognized as a world-class center for wind energy R&D and has many facilities – such as blade structural test stands and a large dynamometer – not otherwise available to the domestic industry or its overseas competitors.

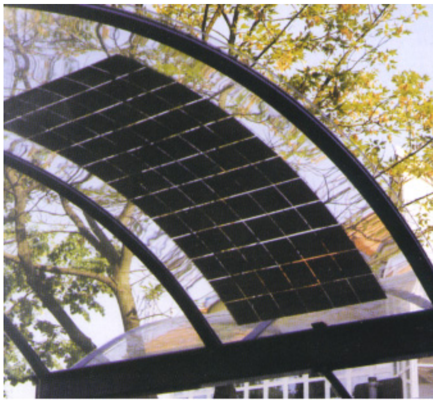
Commercialization and Deployment Activities

- Installed wind capacity expanded by nearly 10% in the United States during 2002 to 4,685 MW, with 410 MW of new equipment going into service. California has the greatest capacity, followed by Texas, Iowa, Minnesota, Washington, Oregon, Wyoming, and Kansas. Worldwide, more than 31,000 MW are installed, and large growth rates illustrate the industry's ability to rapidly increase production with the proper market incentives.
- Wind technology is competitive today in bulk power markets with support from the production tax credit – and in high-value niche applications or markets that recognize noncost attributes. Its competitiveness by 2005 will be affected by policies regarding ancillary services and transmission and distribution regulations. Substantial cost reductions are expected for wind turbines designed to operate economically in low wind-speed sites, which will increase the resource areas available for wind development by 20-fold and move wind generation five times closer to major load centers.

- The principal markets for wind energy are substitution for new natural gas combined-cycle plants (expected to be 97 GW in 2010 and 696 GW in 2030) or displacement of fuel from existing plants, and replacement of coal-generated power plants (expected to be 315 GW in 2010 and 328 GW in 2030).
- Utility restructuring is a critical challenge to increased deployment in the near term because it emphasizes short-term, low-capital-cost alternatives and lacks public policy to support deployment of sustainable technologies such as wind energy.
- In the United States, the wind industry is thinly capitalized, except for General Electric Wind Energy, which recently acquired wind technology and manufacturing assets in April 2002. About six manufacturers and six to 10 developers characterize the U.S. industry.
- In Europe, there are about 12 turbine manufacturers and about 20 to 30 project developers. European manufacturers have established North American manufacturing facilities and are actively participating in the U.S. market.
- Initial lower levels of wind deployment (up to 15%-20% of the total U.S. electric system capacity) are not expected to introduce significant grid reliability issues. Since wind blows intermittently, intensive use of this technology at larger penetrations may require modification to system operations or ancillary services. Transmission infrastructure upgrades and expansion will be required for large penetrations of wind energy to service major load centers.
- Small wind turbine sales are increasing dramatically as a direct result of state incentive programs. California, for example, implemented a rebate of up to $4,500 for the purchase of a wind turbine rated at less than 10 kW. As a result, one small wind turbine manufacturer sold more than 10,000 of their 400 watt and 1,000 watt turbines in 2001 and 2002. About half were sold domestically and half exported. Another manufacturer, whose sales increased 30% in 2002, now has machines ranging from 1 to 10 kW operating in all 50 states and in more than 90 countries.

2.3.2 SOLAR PHOTOVOLTAIC POWER

Technology Description



Semi-transparent PV canopy

PV solar arrays for larger-scale electricity.

PV panels on rooftop.

Solar photovoltaic (PV) arrays convert sunlight to electricity without moving parts and without producing fuel wastes, air pollution, or greenhouse gases. Using solar PV for electricity – and eventually using solar PV for transportation in electric vehicles or by producing hydrogen from water – will help reduce carbon dioxide emissions worldwide.

System Concepts

- Flat-plate PV arrays use global sunlight; concentrators use direct sunlight. Modules are mounted on a stationary array or on single- or dual-axis sun trackers. Arrays can be ground-mounted or on all types of buildings and structures (e.g., see semi-transparent solar canopy, right). The DC output from PV can be conditioned into grid-quality AC electricity, or DC can be used to charge batteries or to split water to produce hydrogen.
- PV systems are expected to be used in the United States for residential and commercial buildings, peak power shaving, and intermediate daytime load following. With energy storage, PV can provide dispatchable electricity and/or produce hydrogen.
- Almost all locations in the United States and worldwide have enough sunlight for PV. For example, U.S. sunlight in the contiguous states varies by only about 25% from an average in Kansas. Land area is not a problem for PV. Not only can PV be more easily sited in a distributed fashion than almost all alternatives (for example, on roofs or above parking lots), a PV-generating station 140 km by 140 km sited at a high solar location in the United States (such as the desert Southwest) could generate all of the electricity needed in the country (2.5×10^6 GWh/year, assuming a system efficiency of 10% and an area packing factor of 50% to avoid self-shading).

Representative Technologies and Status

- Wafers of single-crystal or polycrystalline silicon – best cells: 25% efficiency; commercial modules: 13%-17%. Silicon modules dominate the PV market and currently cost about $2/W$_p$ to manufacture.
- Thin-film semiconductors (e.g., amorphous silicon, copper indium diselenide, cadmium telluride, and dye-sensitized cells) – best cells: 12%-19%; commercial modules: 5%-11%. A new generation of thin-film PV modules is going through the high-risk transition to first-time and large-scale manufacturing. If successful, market share could increase rapidly.
- High-efficiency, single-crystal silicon and multijunction gallium-arsenide-alloy cells for concentrators – best cells: 25%-37% efficient; commercial modules: 15%-24%; prototype systems are being tested in high solar areas in the southwest United States.
- Grid-connected PV systems currently sell for about $5-$8/W$_p$ (20¢-32¢/kWh), including support structures, power conditioning, and land.

Current Research, Development, and Demonstration

RD&D Challenges and Goals

- Improve fundamental understanding of materials, processes, and devices to provide a technology base for advanced PV options.
- Optimize PV cell materials, cell designs, and modules; scale up laboratory cell results to product size (10^4 increase in area).
- Validate new module technologies outdoors and in accelerated testing to achieve 30-year outdoor lifetimes.
- Improve and invent new low-cost processes and technologies; reduce module and balance-of-systems manufacturing costs.
- Address substantial technical issues associated with high-yield, first-time, and large-scale (>100 MW/yr) manufacturing for advanced technologies.
- Develop and validate new, lower-cost systems hardware and integrated applications.
- Meet long-term, cost-competitive goal of manufacturing and installing PV systems under $\$1/W_p$.

RD&D Activities

- Capabilities at national labs and university centers of excellence have been developed, both in expertise and unique facilities. Funding is split 50-50 between national labs and external contracts with universities and industry. Public/private R&D partnerships, including extensive national R&D teams, have been the favored approach. All subcontracts have been awarded via competitive solicitations to select the best and most committed research partners.
- DOE and the National Center for Photovoltaics have worked with state regulatory agencies and influenced the direction of state programs.
- The Department of Defense (DOD) has some funding through special programs in which PV has a role supplying power for military systems.
- The National Aeronautics and Space Administration (NASA) has some research funds for PV. Though this effort has decreased during the past decade, advanced PV has become even more important for space missions (e.g., the high-performance cells on the Sojourner probe on Mars).
- Japan and Europe have significant funding for PV research.
- States have individual subsidy and utility portfolio programs related to PV; for example, California has a buy-down program for residential and commercial PV systems.
- U.S. PV businesses are marginally or not yet profitable and are unable to fund their own advanced research for low-cost PV.

Recent Progress

- Because of public/private partnerships, such as the Thin-Film Partnership with its national research teams, U.S. PV technology leads the world in measurable results such as record efficiencies for cells and modules. Another partnership, the PV Advanced Manufacturing R&D program, has resulted in industry cost reductions of more than 60% and facilitated a sixteen-fold increase of manufacturing capacity during the past 12 years.
- A new generation of potentially lower-cost technologies (thin films) is entering the marketplace. A 25-megawatt amorphous silicon thin-film plant by United Solar is reaching full production in 2005. Two plants (First Solar and Shell Solar) using even newer thin films (cadmium telluride and copper indium diselenide alloys) are in first-time manufacturing at the MW-scale. Thin-film PV has been a focus of the Federal R&D efforts of the past decade because it holds considerable promise for module cost reductions.
- During the past two years, record sunlight-to-electricity conversion efficiencies for solar cells were set by federally funded universities, national labs, or industry in copper indium gallium diselenide (19%-efficient cells and 13%-efficient modules) and cadmium telluride (16%-efficient cells and 11%-efficient modules). Cell and module efficiencies for these technologies have increased more than 50% in the past decade.
- A unique multijunction gallium-arsenide-alloy cell was spun off to the space power industry, leading to a record cell efficiency (35%) and an R&D 100 Award in 2001. This device configuration is expected to dominate future space power for commercial and military satellites.

Commercialization and Deployment Activities
• Worldwide, more than 510 MW of PV were sold in 2002, with systems valued at more than $5 billion; total installed PV is about 2 GW. The U.S. world market share is about 20%. • Worldwide, market growth for PV has averaged 25%/year for the past decade as a result of reduced prices and successful global marketing. In 2001, sales grew 36%, and in 2002, 31%. About two-thirds of U.S.-manufactured PV is exported. • Hundreds of applications are cost effective for off-grid needs. However, the fastest growing segment of the market is grid-connected PV, such as roof-mounted arrays on homes and commercial buildings in the United States. California is subsidizing PV systems to reduce their dependence on natural gas, especially for peak daytime loads which match PV output, such as air-conditioning. **Market Context** • Electricity for remote locations, especially for billions of people worldwide who do not have electricity. • U.S. markets: retail electricity for residential and commercial buildings; distributed utility systems for grid support, peak-shaving, and other daytime uses. • Future electricity and hydrogen storage for dispatchable electricity, electric car-charging stations, and hydrogen production for portable fuel.

2.3.3 SOLAR BUILDINGS

Technology Description

Zero-energy home, the "Solar Patriot."

Solar building technologies deliver heat, light, and cooling to residential and commercial buildings. By combining solar building technologies with solar electric generation (using photovoltaics) and very energy-efficient building envelopes, lighting, and appliances, it is possible to create "Zero Energy Buildings" (see photo for an example demonstration home). Zero-energy buildings have a zero net need for off-site energy on an annual basis.

System Concepts

- In solar heating systems, solar-thermal collectors convert solar energy into heat, usually for domestic hot water, pools, and space heating.
- In solar cooling systems, solar-thermal collectors convert solar energy into heat for absorption chillers or desiccant regeneration.
- In solar lighting systems, sunlight is transmitted into the interior of buildings using glazed apertures, light pipes, and/or optical fibers.

Representative Technologies

- Active solar heating systems use pumps and controls to circulate a heat-transfer fluid between the solar collector(s) and storage. System sizes can range from 1 to 100 kW.
- Passive solar heating systems do not use pumps and controls but rather rely on natural circulation to transfer heat into storage. System sizes can range from 1 to 10 kW.
- Transpired solar collectors heat ventilation air for industrial and commercial building applications. A transpired collector is a thin sheet of perforated metal that absorbs solar radiation and heats fresh air drawn through its perforations.
- Hybrid solar lighting systems focus concentrated sunlight on optical fibers and, with a controller, combine natural daylight with conventional illumination, depending on sunlight availability.

Technology Status/Applications

- Typical residential solar systems use glazed flat-plate collectors combined with storage tanks to provide 40%-70% of residential water heating requirements. Typical systems generate hot water equivalent to supplying 2,500 kWh/year at a cost of about 8¢/kWh.
- Typical solar pool heating systems use unglazed polymer collectors to provide 50%-100% of residential pool heating requirements. Typical systems generate 1,600 therms or 46,000 kWh/year and have 25% of the market.

Current Research, Development, and Demonstration

RD&D Goals

- Near-term solar heating and cooling RD&D goals are to reduce the costs of solar water and space heating systems to 4¢/kWh from their current cost of 8¢/kWh using polymer materials and manufacturing enhancements.
- Near-term, zero-energy building RD&D goals are to reduce the annual energy bill for an average-size home by 50% by 2004 and to zero by 2020.
- Near-term solar lighting RD&D goals are to demonstrate the second generation of the system with an enhanced control system.

RD&D Challenges

- Solar heating and cooling RD&D efforts are targeted to reduce manufacturing and installation costs, improve durability and lifetime, and provide advanced designs for system integration. One key R&D issue is durability. Polymer materials in solar heating systems must survive harsh service environments that include exposure to elevated temperatures, moisture, and ultraviolet radiation.
- Zero-energy building RD&D efforts are targeted to optimize various energy efficiency and renewable energy combinations, integrate solar technologies into building materials and the building envelope, and incorporate solar technologies into building codes and standards.
- Demonstration of hybrid lighting-system performance and reliability in the field are critical to the success of solar lighting.

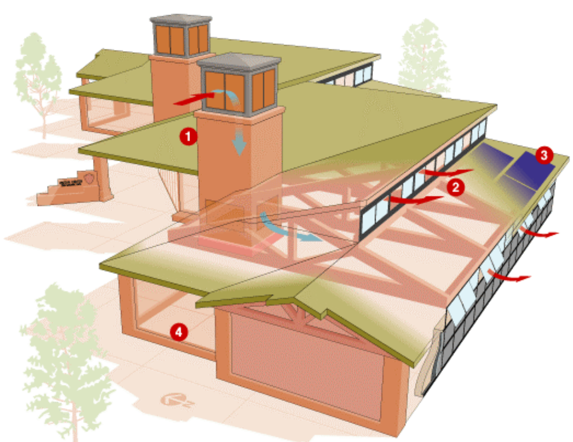
RD&D Activities

- Key DOE program activities are targeted to demonstrate lower cost and improved reliability of components and systems, develop advanced systems and applications, and support the next commercial opportunities for these technologies.
- DOE support of RD&D has been required because solar manufacturers are generally small businesses with limited resources and expertise. These manufacturers are constantly facing manufacturing and system design issues that affect the reliability, lifetime systems costs, and overall cost effectiveness of their products, yet they do not have the resources to conduct reliability and cost-reduction R&D. DOE and its national laboratories, however, have extensive expertise and facilities that can be critical to the long-term success of these manufacturers.

Recent Progress

- More than 1,000 MW of solar buildings PV systems are operating successfully in the United States, generating more than 3 million MWh/year.
- The energy costs of solar-thermal systems have been reduced through technology improvements by more than 50%, saving more than 5 million MWh/yr in U.S. primary energy consumption.

Commercialization and Deployment Activities



Zero-energy buildings require integrated design of the entire building, including energy-saving features, one or more electricity-generating sources, and an energy-management system to monitor and control operations. The Zion National Park Visitor Center, while not totally zero-energy, is one of the Park Service's most energy-efficient buildings.

- About 1.2 million solar water-heating systems have been installed in the United States. However, due to relatively low energy prices, there are currently only approximately 8,000 installations per year.
- Several hundred transpired solar collector systems have been installed, including installations for Ford Motor Company, General Motors, Federal Express, the U.S. Army, and the Bureau of Reclamation.
- Four multidisciplinary and four state-based homebuilding teams have begun the initial phase of designing and constructing Zero Energy Homes for various new construction markets in the United States. One homebuilder, Shea Homes in San Diego, is currently building and selling 300 houses with Zero Energy Home features, including solar electric systems, solar water heating, and very energy-efficient construction.

Market Context

- Retrofit markets: There are 73 million existing single-family homes in the United States. A potential replacement market of 29 million solar water-heating systems is based on the assumption that only 40% of the homes have been built with suitable orientation and absence of shading needed for solar water-heating systems.

- New construction markets: In 2000, 1.2 million new single-family homes were built in the United States. Assuming 70% of these homes could be sited to enable proper orientation of solar water-heating systems, new construction represents another 840,000 possible system installations each year.
- The ultimate market for zero-energy buildings includes both residential and commercial buildings. However, the near-term focus is on residential buildings and, in particular, single-family homes in the Sunbelt areas of the country. Of the1.2 million new single-family homes built in the United States in 2000, 44% of these new homes were in the southern region of the country and 25% were in the western region, which are prime areas for solar buildings and technologies.
- Solar building technologies will reduce daytime peak electricity requirements.

2.3.4 CONCENTRATING SOLAR POWER

Technology Description

Concentrating Solar Power (CSP) systems concentrate solar energy 50 to 5,000 times to produce high-temperature thermal energy, which is used to produce electricity for distributed or bulk generation process applications.

Luz Trough Power Plant

System Concepts

- In CSP systems, highly reflective sun-tracking mirrors produce temperatures of 400°C to 800°C in the working fluid of a receiver; this heat is used in conventional heat engines (steam or gas turbines or Stirling engines) to produce electricity at solar-to-electric efficiencies for the system of up to 30%. Systems using advanced photovoltaics (PV) cells may achieve efficiencies of 33%.
- CSP technologies provide firm, nonintermittent electricity generation (peaking or intermediate load capacity) when coupled with storage.
- Because solar-thermal technologies can yield extremely high temperatures, the technologies could some day be used for direct conversion (rather than indirect conversion through electrochemical reactions) of natural gas or water into hydrogen for future hydrogen-based economies.

Representative Technologies

- A parabolic trough system focuses solar energy on a linear oil-filled receiver to collect heat to generate steam to power a steam turbine. When the sun is not shining, steam can be generated with a fossil fuel to meet utility needs. Plant sizes can range from 1.0 to 100 MW_e.
- A power tower system uses many large heliostats to focus the solar energy onto a tower-mounted central receiver filled with a molten-salt working fluid that produces steam. The hot salt can be stored extremely efficiently to allow power production to match utility demand, even when the sun is not shining. Plant size can range from 30 to 200 MW_e.
- A dish/engine system uses a dish-shaped reflector to power a small Stirling or Brayton engine/generator or a high-concentrator PV module mounted at the focus of the dish. Dishes are 2-25 kW in size and can be used individually or in small groups for distributed, remote, or village power; or in larger (1-10 MW_e) clusters for utility-scale applications, including end-of-line support. They are easily hybridized with fossil fuel.

Technology Status/Applications

- Nine parabolic trough plants, with a rated capacity of 354 MW_e, have been operating in California since the 1980s. Trough system electricity costs of about 12¢-14¢/kWh have been demonstrated commercially.
- Solar Two, a 10-MW_e pilot power tower with three hours of storage, provided all the information needed to scale up to a 30-100 MW commercial plant, the first of which is now being planned in Spain.
- A number of prototype dish/Stirling systems are currently operating in Nevada, Arizona, Colorado, and Spain. High levels of performance have been established; durability remains to be proven, although some systems have operated for more than 10,000 hours.

Current Research, Development, and Deployment

RD&D Goals

- RD&D goals are to reduce costs of CSP systems to 5¢-8¢/kWh with moderate production levels within five years and below 4¢/kWh at high production levels in the long term.

RD&D Challenges

- RD&D efforts are targeted to improve performance and lifetime, reduce manufacturing costs with improved designs, provide advanced designs for long-term competitiveness, and address barriers to market entry.
- Improved manufacturing technologies are needed to reduce the cost of key components, especially for first-plant applications where economies of scale are not yet available.
- Demonstration of Stirling engine performance and reliability in the field are critical to the success of dish/engine systems.

RD&D Activities

- Key DOE program activities are targeted to support the next commercial opportunities for these technologies, demonstrate improved performance and reliability of components and systems, reduce energy costs, and develop advanced systems and applications.
- Several European countries and Israel have programs comparable in size to the United States.
- DOE support of RD&D has been required because of the specialized technology development and the need for reducing costs and for reducing barriers to market penetration. The Federal CSP program provides expert technical support, as well as serving as a catalyst and facilitator for participation of utilities and manufacturers to assist in driving down system costs.

Recent Progress

- New commercial plants are being considered for California, Nevada, and Arizona.
- The 10-MW Solar Two pilot power tower plant operated successfully near Barstow, California, leading to the first commercial plant being planned in Spain.
- Operations and maintenance costs have been reduced through technology improvements at the commercial parabolic trough plants in California by 40%, saving plant operators $50 million.

Commercialization and Deployment Activities

- Parabolic troughs have been commercialized and nine plants (354 MW total) have operated in California since the 1980s.
- The state of Nevada announced plans to build a 50-MW parabolic trough plant near Boulder City. Nevada Power and Sierra Pacific Power will purchase the power to comply with the solar portion of Nevada's renewable portfolio standard.
- Successful operation of Solar Two has provided the basis for a partnership to provide the first 30-100 MW power tower plant.
- The World Bank's Solar Initiative is pursuing CSP technologies for less-developed countries. The World Bank considers CSP to be a primary candidate for Global Environment Facility funding, which could total $1-$2 billion for projects during the next two years.

Market Context

- There is currently 350 MW of CSP generation in the United States, all of it in Southern California's Mojave Desert.
- Power purchase agreements have been signed for 150 MW of new CSP capacity (50 MW in Nevada and 100 MW in Spain). The plants are anticipated to come on-line within the next two to three years. Significant domestic and international interest will likely result in additional projects.
- According to a recent study commissioned by the Department of Energy, CSP technologies can achieve significantly lower costs (below 4¢/kWh) at modest production volumes.
- Congress asked DOE to scope out what would be required to deploy 1,000MW of CSP in the Southwest United States. DOE is actively engaged with the western Governors to map a strategy to deploy 1-5 GW of CSP in the Southwest by 2015.
- A near-term to mid-term opportunity exists to build production capacity in the United States for both domestic use and international exports.

2.3.5 BIOCHEMICAL CONVERSION OF BIOMASS

Technology Description

Biomass resources are agricultural crops and residues, wood residues, grasses, and trees. Biomass absorbs CO_2 as it grows, offsetting the CO_2 emissions from harvesting and processing, and can be a substitute for fossil resources in the production of power, fuels, and chemicals. Biomass feedstocks currently supply about 3 quadrillion Btus (Quads) to the nation's energy supply, based primarily on the use of wood. The potential exists for increasing the total biomass contribution up to 10 Quads nationwide, which would have a positive impact on the farm economy. Cost, sustainable supply availability, biomass variability, and transportation systems are key challenges for biomass utilization. The use of biomass as an alternative to fossil resources reduces most emissions, including emissions of greenhouse gases (GHGs). Through the use of biomass materials that would otherwise go to waste, biomass systems can represent a net sink for GHG emissions because methane emissions that would result from landfilling the unused biomass would be avoided.

Sugars are important platform intermediates for producing fuels, products, and power from biomass. Technologies in manufacturing platforms – such as the sugars platform – can provide the basis for a biorefinery or be combined with those from other platforms. The sugars platform is used to break down biomass, cellulose, and hemicellulose polymers into their building blocks. The building blocks are sugars that can be converted to many products including liquid fuels (e.g., ethanol), monomeric components for the polymer market (e.g., lactic acid), and hydrogen. In addition to the sugars platform, DOE is working on the glyceride platform, which uses biomass rich in vegetable oil (oil seeds like soybean) and converts the oil into esters that can be combusted like petroleum-based diesel. Other valuable biobased products can be produced from this conversion as well.

The biorefinery is analogous to an oil refinery. Multiple feedstocks are converted to a slate of products via multiple technology routes. Fuel production provides a large-volume product to achieve economies of scale, while lower-volume biobased coproducts and power can improve the economic competitiveness of biomass as a sustainable source of energy. Integrated biorefinery systems are being evaluated for their feasibility in producing fuels and products for potentially large commercial markets. A major challenge is to develop the ability to convert the fractionated biomass components into value-added products as efficiently as the current petrochemical business.

System Concepts

- The most common sugar-platform process consists of pretreating a biomass feedstock to release sugars from the fibrous cellulose and hemicellulose fractions. These sugars can be converted biologically into products such as ethanol or lactic acid, and can also be converted catalytically into products such as sorbitol. The products are then purified and sold as liquid fuels, sold into commodity chemical markets, or further converted and sold into other markets. The residue remaining from the sugar process can be burned to produce steam and electricity or further processed into other products such as animal feed.
- The glyceride platform consists of squeezing oil from an oil seed and transesterifying the oil to produce esters and glycerol. The esters can be purified for use as a liquid fuel (biodiesel), and purified glycerol can be sold as a commodity chemical or converted to other products (e.g., 1,3 propanediol).

Representative Technologies

- Sugar platform: hydrolysis of fibrous biomass that utilizes enzymes or acid catalysts, followed by microbial or catalytic conversion of the sugars to products.
- Glyceride platform: thermochemical transesterification of triglycerides.

- Fractionating biomass materials from grain and oil seeds, agricultural and forestry residues, or dedicated biomass feedstocks (such as grasses and woody crops) into component parts allows further development of value-added products such as chemical intermediates, wood products, biodiesel fuel, and composite materials.

Technology Status/Applications

- Acid hydrolysis: This sugar-platform technology is mature, with only the recovery of acid to be proven at industrial scale. One DOE partner is working with local and state governments to plan and design a facility that would separate MSW and convert its biomass portion to fuel-grade ethanol.
- Enzymatic hydrolysis: A major barrier of this sugar-platform technology has been development of low-cost cellulase enzyme cocktails. DOE has cost-shared subcontracts with Genencor International and Novozyme Biotech to reduce the cost of enzymes to improve the economics of the process. Process options using those enzymes will lead to the first large-scale, sugar-platform biorefineries.
- R&D advances have been identified to lower the cost of sugars for products including biofuels. As production costs for biofuels are reduced commensurately, larger fuel markets will become accessible. The technical challenge is to advance biomass processing to a level of maturity comparable to that of the existing petroleum industry.
- Glyceride platform: Many small glyceride facilities exist. The technology challenge is to convert batch-type facility designs to continuous processes that are built with greater capacity. Larger, continuous facilities will produce diesel products that can better compete with crude oil-based diesel. Development of coproducts also will help.
- Biobased products will be key elements in the development of integrated processes for producing fuels, chemicals, and power from both the sugar and glyceride platforms.

Current Research, Development, and Demonstration

RD&D Goals

By 2005

- Enzyme industry partners will provide new cellulase enzymes that are 10 times more cost effective than what is commercially available today.

By 2010

- Technologies will be developed for producing ethanol from cellulosic feedstocks at $1.29/gallon or less.
- Government will work with U.S. industry to introduce up to four new biobased chemical intermediate processing systems.
- Technologies will be developed for producing a mixed sugar stream from cellulosic feedstocks at $0.07/lb.

RD&D Challenges

- Low-cost enzymatic hydrolysis process technologies need to be developed.
- Pretreatment cost, yield, and equipment reliability need to be improved.
- Process integration and optimization needs to be developed.
- Fermentation organisms need to be developed and improved.

RD&D Activities

- Evaluation of pretreatment options and advanced R&D to understand biomass feedstock mechanisms.
- Industrial partnerships for demonstrating biochemical conversion technology on corn stover.
- Joint DOE and USDA solicitations targeting key enabling technologies to meet the RD&D challenges.

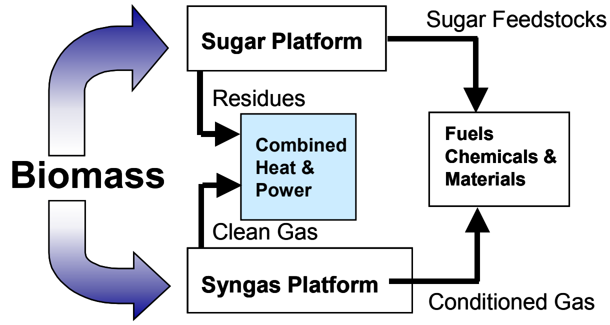
Recent Progress

- Cargill-Dow, a corporate partner, has built a facility that can produce almost 300 million pounds of lactic acid annually from corn starch. The facility also converts lactic acid into PLA for the polymers markets.
- Genencor International has announced that it met the target of a 10X reduction in the cellulase portion of the production cost of ethanol from biomass. Novozyme Biotech has announced that it expects to achieve the same goal by the end of its subcontract in 2004.
- Breakthroughs in genetically engineered microorganisms capable of fermenting the broad range of sugars found in biomass. These advances have led to an R&D 100 award and a number of patents.

• A conceptual design and cost estimate of a cellulosic ethanol facility has been completed and updated by DOE and engineering and construction firms. The report outlines the process necessary to meet cost targets.
Commercialization and Deployment Activities
• Conversion of cellulosic biomass to sugars and products from those sugars is not yet commercial. The U.S. capacity to produce ethanol from corn is 3 billion gallons annually. Ethanol is used as a fuel extender and, increasingly, as an oxygenating additive for reformulated gasoline wherever MTBE is phased down. • Starch crops play a transitional role, but large-scale displacement of petroleum will rely on cellulose. • About 15-21 million gallons of biodiesel is produced annually in the United States. • Biobased products can replace 1:1 their chemically derived counterpart if the cost is competitive. This approach is of interest to the existing biomass-processing community; their infrastructure is already in place. • Oil-based products or fuels have essentially a 1:1 displacement of petroleum-based products or fuels; this is attractive in efforts to reduce dependence on imported oil. • Biobased products can bring new properties and functions to materials and chemical intermediates. This characteristic can enable biorefinery operations and the development of small businesses. Here, the market is not fully defined, capital risk is high, and time to commercialize may be long. Investments by the Federal government can lower some of these barriers. **Market Context** • For ethanol: 1 Quad of biomass: 1% of projected petroleum imports for 2020 5 Quads of biomass: 6% of projected petroleum imports for 2020 • For fuels and chemicals (depending on the mix of products): 1 Quad of biomass: 0.5-1% of projected petroleum imports for 2020 5 Quads of biomass: 5-10% of projected petroleum imports for 2020

2.3.6 THERMOCHEMICAL CONVERSION OF BIOMASS

Technology Description



Biomass resources are agricultural crops and residues, wood residues, grasses, and trees. Biomass absorbs CO_2 as it grows, offsetting the CO_2 emissions from harvesting and processing, and can be a substitute for fossil resources in production of power, fuels, and chemicals. Biomass feedstocks currently supply about 3 quadrillion Btus (Quads) to the nation's energy supply based primarily on wood resources. The potential exists for increasing total biomass contribution to 10 Quads nationwide, which would create positive impacts on farming and forest products industries. Cost, sustainable supply availability, biomass variability, and delivery systems are key challenges for biomass utilization. Use of biomass resources as an alternative to fossil resources reduces most emissions, including emissions of greenhouse gases (GHGs). Through use of materials that would normally be waste, biomass systems bring about a net sink for GHG emissions, because methane emissions that would result from landfilling are avoided.

Thermal conversion of biomass is a manufacturing platform comprised of many technology routes and involves use of heat to break down biomass feed into an oil-rich vapor in pyrolysis and/or synthesis gas in gasification, which is used for generation of heat, power, liquid fuels, and chemicals. Technologies in this platform can provide the basis for a biorefinery, or be combined with other platform technologies. One advantage of thermal conversion processes is that they can convert nearly all biomass feedstocks into synthesis gas, including some feedstock components that are difficult to process by chemical or biological means.

The biorefinery is analogous to an oil refinery. Multiple feedstocks are thermally converted to a slate of products via multiple technology routes. Fuel production provides a large-volume product to achieve economies of scale, while lower volume biobased coproducts and power can improve the economic competitiveness of biomass as a sustainable source of energy. Integrated biorefinery systems are being evaluated for their feasibility in producing fuels and products for potentially large commercial markets. A major challenge is to develop the ability to convert the fractionated biomass components into value-added products as efficiently as the current petrochemical business of today.

Biomass combustion is a thermal process that converts biomass entirely to carbon dioxide and water vapor; and, thus, precludes conversion to intermediate fuels or chemicals. The existing biomass power industry primarily uses combustion to produce steam for heat and electricity generation. Co-combustion of biomass with coal, or "cofiring" has received recent interest as a way to reduce fossil carbon emissions from coal power plants. There are few significant technical barriers to increase use of these technologies.

System Concepts and Representative Technologies

Thermal conversion technology is important and has several key roles in an emerging bioeconomy:

- Most current biomass conversion is for heat and power generation and is based on direct combustion in small, biomass-only plants with relatively low electric efficiency of about 20%. Technology exists so that total system efficiencies can approach 90% if combined heat and power systems are applied. Most biomass direct combustion generation facilities use the basic Rankine steam cycle for electric power generation, which is made up of a steam boiler, an electric turbine, a condenser, and a pump. Evolution of combined cycles that integrate the use of gas and steam turbines can increase generation efficiency by up to two times. Cofiring of biomass with coal also can increase overall biomass-to-electricity conversion efficiency.
- A source of syngas for catalytic production of fuels, chemicals, and hydrogen is important. Once a clean synthesis gas is obtained, it is possible to access and leverage mature process technologies developed in the petroleum and chemicals industry for the production of a wide range of liquid fuels and chemicals.
- A source of heat and power for biorefinery operation. Virtually all other conversion processes – whether physical or biological – produce residue that cannot be directly converted to the primary product(s). In order to mitigate waste streams and to maximize the efficiency of the biorefinery, these residues can and

should be used for heat and power production. In existing biorefineries, residues are combusted in a steam boiler. There is a technological opportunity however, to use a gasifier coupled to a gas turbine combined cycle that can double conversion efficiency to electricity, while still producing steam from the gas turbine waste heat. Use of a biomass gasifier in a gasifier combined-cycle system can leverage on public and private investments in development of advanced- and next-generation gas turbine systems (more than $1 billion).

- Thermal conversion is a way to derive additional value from process residues. Within a biorefinery, thermal conversion and gasification can push many residues "up the value chain" through production of hydrogen or other higher-value products via thermal conversion to syngas followed by separation or synthesis steps.
- Gasification converts biomass to a syngas that can be substituted for natural gas in combustion turbines, shifted into hydrogen for fuel cell or other applications, or used in existing commercial catalytic processes for production of liquid fuels and chemicals. Several technologies exist in various stages of development for production of a suitable syngas, including indirect gasification, steam reforming of biomass, and gasification with oxygen or enriched air.
- Pyrolysis of biomass produces an oil-rich vapor that can be condensed for direct use as a fuel or as a hydrogen carrier, or refined for producing a variety of higher-value chemical products.

Technology Status/Applications

- The existing biopower sector, nearly 1,000 plants, is mainly comprised of direct combustion plants, with an additional small amount of cofiring (approximately 400 MW_e). Plant size averages 20 MW_e, and the biomass-to-electricity conversion efficiency is about 20%. Grid-connected electrical capacity was 9,700 MW_e in 2001; more than 75% of this power is generated in the forest products industry's combined heat and power applications for process heat. Combined utility and industrial generation in 2001 was more than 60 billion kilowatt-hours (about 75% of nonhydro renewable generation). Recent studies estimate that on a life-cycle basis, existing biopower plants represent a net carbon sink of 4 MMTC/yr. Biopower electricity prices generally range from 8¢–12¢/kWh.
- U.S. investment in equipment is $300-$500 M/year. At least six major engineering procurement and construction companies and several multinational boiler manufacturers are active.
- Biomass cofiring with coal ($50–$250/kW of biomass capacity) is the most near-term option for large-scale use of biomass for power-only electricity generation. Cofiring also reduces sulfur dioxide and nitrogen oxide emissions. In addition, when cofiring crop and forest product residues, GHG emissions are reduced by a greater percentage (e.g. 23% GHG emissions reduction with 15% cofiring).
- Small biopower and biodiesel systems have been used for many years in the developing world for electricity generation. OE is developing systems for village power applications for distributed generation that are more efficient, reliable, and clean for the developed world. These systems range in size from 3 kW to 5 MW, with field verification completed by the end of 2003.

Current Research, Development, and Demonstration

RD&D Goals

By 2005

- Resolve tar issues through integrated testing of candidate materials, catalysts, and technologies at appropriate scale.
- Verify hydrogen-production system and fuel cell operation.

By 2010

- Validate integration of gas treatment system with syngas-based biorefinery.
- Validate integration of hydrogen production or fuel cell operation with syngas-based biorefinery.
- Validate distributed fuels and chemicals production through industrial demonstration projects. Help the U.S. industry to introduce up to four new biobased chemical intermediate processing systems.By 2015
- Validate integrated syngas biorefineries through industrial demonstration projects.

RD&D Challenges

- Feed Preparation/Gasification – Improved feed processing for operational reliability need to be developed.
- Gas Cleanup – Improved methods of removing contaminants from syngas and modifying gas composition are needed.
- Synthesis gas utilization – The feasibility and optimization of syngas use in fuels, chemicals, and heat/power applications needs to be demonstrated on both a laboratory and industrial pilot scale.
- System Integration – Careful integration of the entire conversion system to maximize efficiency and reduce costs is needed.
- Development of enabling technologies is needed so that industry can reduce their risk of development and reduce development-cycle time.
- Verification and quantification of environmental and other benefits of themochemically derived fuels and chemicals is needed.

RD&D Activities

- Core research in feed preparation and handling, gasification, gas cleanup and conditioning, syngas utilization, and sensors and controls.
- Solicitation(s) for industry and university core research in targeted areas addressing specific barriers, e.g., high-pressure feeder development, novel gasification concepts, gas cleanup, hydrogen production, and sensors and controls.
- Solicitation(s) for precommercial validation of integrated processes for distributed fuels, chemicals, and hydrogen; and for integrated biorefinery applications.
- Joint DOE and USDA solicitations targeted to key enabling technologies can have an impact on meeting RD&D challenges.
- USDA has extensive research in crop production and is beginning to fund community-based, small-system demonstrations in collaboration with DOE.

Recent Progress

- R&D 100 award for the Burlington, Vermont, gasifier (Future Energy Resources Corporation, Battelle, and DOE Labs).
- Successfully demonstrated NO_x reductions from cofiring in excess of cofired percentage.
- Completed life-cycle assessments verifying and quantifying environmental benefits of biopower systems.
- Successful energy crop (switchgrass and willow) harvesting and cofiring in Iowa, Louisiana, and New York.
- Public release of modeling software (BIOCOST) that allows evaluation of energy crop production cost scenarios.
- Annual switchgrass yields of more than 10 t/acre obtained from best test plots in three southern states.
- Successful collaboration between private industry, DOE, and the USDA-Forest Service to demonstrate the small-scale modular production of heat and power in community settings (schools, small businesses).
- Demonstration at commercial prototype scales the use of biomass-derived resins from bark for engineered wood products.

2.3.7 BIOMASS RESIDUES

Technology Description
Biomass residues are the organic byproducts of green plants used for food, fiber, and forest production and processing. Major sources of residues include grain crops such as corn, wheat, and rice; animal waste; forest harvest; fuel-reduction treatments, and processing. These residues can be used as an alternative fuel source and for other purposes. This profile addresses the issues of harvesting, storing, and transporting biomass residues. **System Concepts** • The sustainable use of biomass residues for energy requires understanding when and where residues can be removed from agricultural and forest soils without reducing long-term productivity. • Under certain circumstances, residues may have greater economic and ecological value when left on the land to restore nutrients, reduce erosion, and stabilize soil structure than if harvested for fuel. Biomass residue energy production may be most effective in locations where crop yields and soil organic levels are high, and erosion is not a major concern. **Representative Technologies** • Agricultural residues (corn stover, straws from wheat, rice, and other grain crops). • Wood residues resulting from lumber, furniture, and fiber production. • Forest residues (tops and limbs from harvest for wood products, material from fuel reduction treatments). • Black liquors from pulp production. • Animal wastes from confined production of chickens, pigs, and cows. • Clean wood from urban yard trimmings and construction/demolition. **Technology Status/Applications** • Sustainable and recoverable amounts of corn stover, wheat straw, rice straw, and cotton stalks are estimated at about 150 MdT/year (less than 50% of the amount actually produced). Some corn stover is being removed presently for production of chemicals and animal bedding. Straws are being used in Europe as a bioenergy resource. • More than 2.1 quadrillion Btu of primary biomass energy is consumed by industry, and it generates 56 million MWh of electricity plus heat. Nearly two-thirds of this electricity is derived from wood and wood wastes (including spent pulping liquors, wood residues, byproducts from mill processing, and forest residues). About one-third of the electricity and heat is derived from municipal solid waste and landfill gas. • Some technologies are available to combust or gasify animal wastes. The most widely known option is to capture methane gas, a byproduct of anaerobic digestion.
Current Research, Development, and Demonstration
RD&D Goals • By 2004, obtain measurable cost reductions in corn-stover supply systems with modifications of current technology. • By 2007, develop whole-crop harvest systems for supplying biorefineries to make multiple products. • By 2010, develop a system of whole-crop harvest and fractionation for maximum economic return, including returns to soil for maximum productivity and conservation practices. • By 2015, develop an integrated system for pretreatment of residues near harvest locations and a means of collecting and transporting partially treated substrates to a central processing operation. • By 2020, develop fully integrated crop and residue harvesting, storage, and transportation systems for food, feed, energy, and industrial applications. **RD&D Challenges** • Develop environmental data to make decisions on residue removal from agricultural and forest lands. • Assemble better information on the characteristics of residue feedstock to assist in cost-effective harvest/handling and storage systems, and to assist potential users in optimizing their systems to handle residue feedstock. • Develop cost-effective drying, densification, and transportation techniques to create more “standard” feedstock from residues.

- Develop efficient and environmentally sound infrastructure for residue supply systems (collection, handling, storage, transport).
- Gain public acceptance for the removal of agricultural and forest residues where shown to be sustainable.
- Develop methods for estimating residue availability based on published or easily accessible information sources.
- Develop effective and publicly acceptable ways of using animal wastes.

RD&D Activities

- Reduce feedstock costs and enhance feedstock quality through improving and adapting the existing collection, densification, storage, transportation, and information technologies (precision agriculture and forestry) to bioenergy supply systems.
- Enhance the sustainability of feedstock supply enterprises (production and handling) by developing and servicing robust machines for multiple applications and extended use.
- Research the engineering properties of novel aqueous and nonaqueous multiphase bioenergy feedstocks.

Recent Progress

- Critical operations contributing to the cost of residue harvest have been identified. It is now clear that a reduction in the number of operations is the key to reduction in feedstock costs.
- Farm-equipment manufacturers in the United States are becoming increasingly aware of opportunities in biomass harvesting and handling systems. Large and small companies are building alliances with research institutions to develop equipment for handling large quantities of biomass.
- Green power producers are making greater use of landfill gas as a resource for electricity production.

Commercialization and Deployment Activities

- Use of biomass residues for bioenergy and bioproducts is already commercial where those materials are captured internally by an industry or where disposal fees are high enough to encourage delivery of these materials to an energy end user for little to no cost.

2.3.8 ENERGY CROPS

Technology Description

Energy crops are fast-growing, genetically improved trees and grasses grown under sustainable conditions for harvest at 1 to 10 years of age. End uses of energy crops include biomass power (combustion and gasification), biofuels (ethanol), and new bioproducts such as plastics and many types of chemicals.

System Concepts

- Biomass feedstock supply systems are widely available throughout the United States but locally optimized for climate and soil conditions and end-use requirements.
- Quantities must be sufficient to support large-scale processing facilities.
- In the future, some crops will likely be genetically tailored in a way that facilitates separations and conversion processes for selected end uses.

Representative Technologies

- Short rotation woody crops – selected tree varieties grown as single-stem trees under sustainable conditions for year-round harvest within 4-10 years with replanting assumed.
- Woody coppice crops – selected tree varieties grown as multistemmed “bushes” under sustainable conditions for year-round harvest.
- Perennial grass crops – selected high-yield varieties of grasses grown under agronomic conditions for fall and winter harvest with stand regrowth assumed for up to 10 years, involving some modification to standard forage harvest systems.
- Genetic improvement, pest and disease management, sustainability optimization, and harvest equipment development R&D ongoing for all of the above.

Technology Status/Applications

- Short-rotation woody crops are produced commercially in the Pacific Northwest and North Central regions of the United States and many parts of the world (Brazil, Australia, Spain, etc.) for combined fiber and energy use.
- Woody coppice crops are produced commercially in Northern Europe and are being adapted to and tested at an operational scale in New York.
- Perennial grass crops have high yield potential and have been demonstrated in south, southeastern, mid-west, and north-central parts of the United States. Technology is being tested as a biomass feedstock supply system for biomass power in Iowa.

Current Research, Development, and Demonstration

RD&D Goals

- By 2005, develop feedstock crops with experimentally demonstrated yield potential of 6-8 dry ton/acre/year.
- By 2005, develop cost-effective, energy-efficient, environmentally sound harvest methods.
- By 2010, identify genes that control growth and characteristics important to conversion processes in few model energy crops.
- By 2010, improve understanding of biotechnology impacts on environment and ecology.
- By 2010, achieve low-cost, “no-touch” harvest/processing/transport of biomass to process facility.
- By 2020, increase yield of useful biomass per acre by a factor of 2 or more compared with year 2000 yields.
- By 2020, energy crops will be contributing strongly to meeting biomass power and biofuels production goals.

RD&D Challenges

- Transfer genomics information gained from arabidopsis, rice, and corn to acceleration of domestication of poplars and switchgrass.
- Develop gene maps and increased functional genomics understanding for model crops.
- Develop an efficient infrastructure for energy crop supply and utilization systems.
- Scale up seed to large-scale commercial deployment.

- Demonstrate that energy crop production is sustainable and environmentally beneficial.
- Gain acceptance by the public for the use of genetic engineering of energy crops.
- Develop expertise on machinery and logistics aspects of agricultural and forest engineering.

RD&D Activities

- Crop yield improvement research on two model woody crops (poplars and willow) and one herbaceous species (switchgrass) is being conducted by researchers in academic and USDA research organizations in many locations throughout the country.
- Genetic maps have been developed for poplars and are in process for switchgrass; work has been initiated to identify genes important to accelerated domestication of poplars and switchgrass.
- Cost-supply relationships are being generated for energy crop supplies in different regions of the country.
- Environmental research to optimize energy crop sustainable production techniques is being conducted in a few locations.
- Research on control of diseases and pests through genetics and/or cultural management.

Recent Progress

- Yields of up to 10 dry tons/acre/year have been observed in small experimental plantings of poplars, willows, and switchgrass in selected locations with genetically superior material.
- Yields of 5-7 dry tons/acre/year have been measured in small pilot-scale regional field trials of energy crops in some locations.
- Two major industrial enzyme companies are developing a new generation of cellulase enzymes to support an enzyme sugar platform.
- Farmers are engaged in energy crop R&D in several regions of the country through Federally supported demonstrations.
- An economic model for energy crop production costs has been released for public use.
- Joint USDA/DOE analysis on the economic impacts of bioenergy crop production on U.S. agriculture has shown the potential for net farm income to increase from $2.8 billion to $6 billion depending on production scenarios and feedstock prices.
- A nutrient cycling spreadsheet model applicable to forestry and short rotation woody crop applications has recently been completed and made available to industry and the public on the Web.

Commercialization and Deployment Activities

- Between 1983 and 1998, 70,000 acres of poplars were established commercially in the Pacific Northwest with significant utilization of new hybrid materials generated by the DOE-funded research programs. Opportunistic market conditions, together with short-rotation crop technology readiness and technology transfer activities, were all critical to the commercialization success in the Pacific Northwest.
- Other types of short-rotation crops – including eucalyptus, sweetgum, sycamore, and willow, and established in other parts of the country – contribute to an approximate total level of commercialization of short-rotation woody crops of about 120,000 acres. Willow contributes a partial wood supply to a cofiring biomass power demonstration project. Switchgrass is already a crop planted on many Conservation Reserve Program acres, and it is the feedstock supply for two biomass power cofiring demonstrations.

2.3.9 PHOTOCONVERSION

Technology Description

Photoconversion technology encompasses sunlight-driven quantum-conversion processes (other than solid-state photovoltaics) that lead to the direct and potentially highly efficient production of electrical power or fuels, materials, and chemicals from simple renewable substrates such as water, carbon dioxide (CO_2) and nitrogen. This technology has the potential to eliminate the need for fossil fuels by substituting renewable sources and conversion processes that are either carbon neutral (any carbon generated is reused during plant growth) or carbon free (e.g., hydrogen from water). These technologies also can convert CO_2 into liquid and gaseous fuels via processes that are often termed biomimetic, or bio-inspired.

A photoconversion process to produce hydrogen from metabolically engineered algae.

System Concepts

- Photoconversion processes use solar photons directly to drive biological, chemical, or electrochemical reactions to generate electricity, fuels, materials, or chemicals.
- System components include biological organisms or enzymes, semiconductor structures (photoelectrochemical cells, colloids, nanocrystals, certain plastics or polymers, quantum dots or nanoparticles, or superlattices), biomimetic molecules, dye molecules, synthetic catalysts, or combinations of the above.

Representative Technologies

- Elements of this future solar technology include photobiological, photochemical, photoelectrochemical, photocatalytic, and dark catalytic processes for energy production.
- Photoconversion technologies can produce electrical power, hydrogen, biodiesel, organic acids, methane, methanol, and plastics. These technologies also can remove CO_2 from the atmosphere through photoreduction of CO_2 to fuels, materials, and chemicals. Moreover, they can achieve atmospheric nitrogen fixation (independent of natural gas) and convert biomass to fuels, materials, or chemicals.
- Most of these technologies are at early stages of research, but some are at the development level, and some that produce high-value products are commercial.

Technology Status/Applications

- Power production: dye-sensitized, nanocrystalline, titanium dioxide semiconductor solar cells are 8%-11% efficient and are potentially very cheap. In contrast to solid-state PV solar cells, light is absorbed by dye molecules in contact with an electrolyte rather than solid-state semiconductor materials. Novel photoelectrochemical cells with integrated fuel cells and in situ storage for 24-h solar power have been demonstrated at 6%-7% efficiency in 4-by-8-foot panels using a system developed by Texas Instruments, and photochargeable batteries that include electrochemical storage have been demonstrated with 24-h power output. Hot-carrier photoconversion technology for increasing solar-conversion efficiencies (with theoretical efficiency limits of 65%-86%, depending on the solar photon concentration) is making progress. The term "hot carrier" refers to the utilization of highly energetic electrons (called hot electrons and created upon absorption of photons with energies larger than the semiconductor bandgap) for useful chemical production or electrical power, rather than converting the excess electron energy to heat by photon emission. In present photoconversion and photovoltaic devices, the hot electrons cool, and their excess energy is lost as heat in a picosecond (1E-12 sec) or less. Semiconductor nanostructures have been found to slow the cooling time of hot electrons by up to two orders of magnitude, thus enhancing the probability for hot electron conversion.

- Fuels production: Photoelectrochemical and photobiological processes that will lead to hydrogen production from water or gasified biomass are at the early stages of research, and important advances have been made recently; biodiesel, methane, and methanol production from water, waste, and CO_2 are at various stages of R&D; and fuels, such as methanol – produced by the direct electrocatalytic or photocatalytic reduction of CO_2 – are at the early fundamental research stage. Electrocatalytic concentration of CO_2 from the atmosphere is being studied as well; it is of interest to people involved in atmospheric control in small spaces (i.e., submarines and the space station) and has potential for removing CO_2 from the atmosphere in the future.
- Materials and chemicals production: Producing materials and chemicals from CO_2 and/or biomass, as well as producing fertilizer from atmospheric nitrogen and renewable hydrogen, will reduce CO_2 emissions compared with the fossil fuels used currently.
- Photobiological production of pigments (e.g., astaxanthin), health foods, nutritional supplements (e.g., omega-3 fatty acids), protein, and fish food is commercial. Production of biopesticides and pharmaceuticals is under development. Production of commodity chemicals such as, but not limited to, glycerol, hydrogen peroxide, and bioemulsifiers is possible. Photocatalytic production of specialty or high-value chemicals has been demonstrated.

Current Research, Development, and Demonstration

RD&D Goals

- Most photoconversion technologies are at the fundamental research stage, where technical feasibility must be demonstrated before cost and performance goals can be assessed. Minimum solar conversion efficiencies of 10% are generally thought to be necessary before applied programs can be considered. Cost goals need to be competitive with projected costs of current technologies.
- Electrical power and high-value chemicals applications are either currently commercial or will see dramatic growth during the next 5-10 years. Large-scale power production should begin in 2010-2015. Materials and fuels production will begin in 2015-2020, and commodity chemicals production begins in 2020-2030.

RD&D Challenges

- Develop the fundamental sciences in multidisciplinary areas involving theory, mechanisms, kinetics, biological pathways and molecular genetics, natural photosynthesis, materials (semiconductor particles and structures), catalysts and catalytic cycles, and biomimetic components. Progress in fundamental science is needed to underpin the new photoconversion technologies.
- Maintain critical mass research groups in vital areas long enough for sustained progress to be made.

RD&D Activities

- A significant level of basic research activities in solar photoconversion is currently being performed by the DOE Office of Science; some exploratory R&D is being performed by DOE Office of Energy Efficiency and Renewable Energy/Office of Solar Technologies.
- Some basic research support by the National Science Foundation and the U.S. Department of Agriculture is complementary.

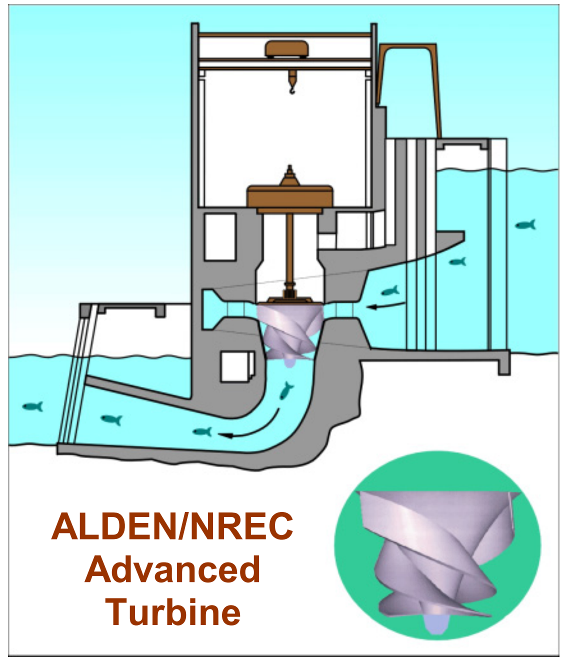
Recent Progress

- Prototype dye-sensitized nanocrystalline semiconductor solar cells have been demonstrated as power sources in small niche markets. Commercial interest is very high because they also can be configured to produce hydrogen.
- Scientific breakthroughs during the past seven years have been made in microbial and enzymatic R&D; natural photosynthesis; semiconductors, nanostructures, quantum dots, and superlattices; CO_2 catalysis; and energy and electron transfer in artificial donor/acceptor molecules.

Commercialization and Deployment Activities
• Astaxanthin, a pigment synthesized from petroleum, is used as a coloring agent in the poultry and salmon industries. Algal production of the pigment just started in Hawaii and is replacing the fossil version for health and environmental reasons. Large-scale algal ponds are producing high-value chemicals on a commercial basis using photobiological processes. As an example, the current astaxanthin market is $180 M/year and is expected to rise to $1 B/year in five years. • European and Japanese companies are beginning to commercialize dye-sensitized, nanocrystalline cell-powered watches. The market is estimated to be 100 million units. **Market Context** • Besides the applications discussed above, many spin-off technologies are possible. These include optoelectronics, biosensors, biocomputers, bioelectronics, and nanoscale devices.

2.3.10 ADVANCED HYDROPOWER

Technology Description



Hydroelectric power from falling water generates no greenhouse gas. To the extent that existing hydropower can be maintained or expanded by addressing environmental concerns through advances in technology, it can continue to be an important part of a greenhouse gas emissions-free energy portfolio. Advanced hydropower is technology that produces hydroelectricity both efficiently and with improved environmental performance. Traditional hydropower may have environmental effects, such as fish mortality and changes to downstream water quality and quantity. The goal of advanced hydropower is to maximize the use of water for generation while eliminating these environmental side effects.

System Concepts

- Conventional hydropower projects use either impulse or reaction turbines to convert kinetic energy in flowing or falling water into turbine torque and power. Source water may be from free-flowing rivers, streams, or canals, or water released from upstream storage reservoirs.
- New environmental and biological criteria for turbine design and operation are being developed to help sustain hydropower's role as a clean, renewable energy source – and to enable upgrades of existing facilities and retrofits at existing dams.

Representative Technologies

- New turbine designs that improve survivability of fish that pass through the power plant.
- Autoventing turbines to increase dissolved oxygen in discharges downstream of dams.
- Reregulating and aerating weirs used to stabilize tailwater discharges and improve water quality.
- Adjustable-speed generators producing hydroelectricity over a wider range of heads and providing more uniform instream-flow releases without sacrificing generation opportunities.
- New assessment methods to balance instream-flow needs of fish with water for energy production and to optimize operation of reservoir systems.
- Advanced instrumentation and control systems that modify turbine operation to maximize environmental benefits and energy production.

Technology Status/Applications

- Hydropower provides about 78,000 MW of the nation's electrical-generating capability. This is about 80 percent of the electricity generated from renewable energy sources.
- Existing hydropower generation faces a combination of real and perceived environmental effects, regulatory pressures, and changes in energy economics (deregulation, etc.); potential hydropower resources are not being developed for similar reasons.
- Some new environmentally friendly technologies are being implemented (e.g., National Hydropower Association's awards for Outstanding Stewardship of America's Rivers and the Tennessee Valley Authority's (TVA's) Lake Improvement Program).
- DOE's Advanced Hydropower Turbine System (AHTS) program is working through public-private partnerships with industry to demonstrate new turbine designs are feasible.

Current Research, Development, and Demonstration

RD&D Goals

- By 2010: Complete testing of a commercially viable hydroelectric turbine technology capable of reducing the rate of fish mortality to 2%, which is equal to or better than other methods of fish passage (e.g. spillways or fishways).

- By 2010: Complete the development of Advanced Hydro Turbine Technology in support of maintaining hydroelectric generation capacity due for relicensing between 2010 and 2020.

RD&D Challenges

- Biological design criteria for new technology are limited by poor understanding of how fish respond to turbulent flows and other physical stresses inside turbines and downstream of dams.
- To affect public perception, field-testing will be needed to provide the evidence that fish survival through turbines is equal to or greater than survival in other passage routes around dams. Regulatory trends are shifting power plant operation from peaking to baseload, effectively reducing the energy value of hydroelectricity and reducing plant capacity factors; higher instream-flow requirements are reducing total energy production to protect downstream ecosystems, but scientific justification is weak.

RD&D Activities

- DOE's AHTS program constructed a test facility for pilot-scale testing of a new turbine design to evaluate hydraulic and biological performance; testing at this facility was completed in FY 2003.
- New biological design criteria to protect fish from shear and pressure have been developed in controlled laboratory experiments; computational fluid dynamics modeling and new sensor systems are producing new understanding of turbulence in turbines and draft tubes.
- Regional efforts by the Army Corps of Engineers and Bonneville Power Administration are producing solutions to some site-specific problems, especially in the Columbia River basin; but they are not addressing the national situation that is driven by market pressures and environmental regulation.
- Resource assessments of low-head and low-power resources are being conducted.

Recent Progress

- TVA has demonstrated that improved turbine designs, equipment upgrades, and systems optimization can lead to significant economic and environmental benefits – energy production was increased approximately 12% while downstream fish resources were significantly improved.
- Field-testing of some features of the Kaplan turbine Minimum Gap Runner design indicates that fish survival can be significantly increased, if conventional turbines are modified. The full complement of Minimum Gap Runner design features have not been implemented in a single turbine, so additional performance improvements are expected.

Commercialization and Deployment Activities

- Voith Siemens Hydro Power and the TVA have established a partnership to market environmentally friendly technology at hydropower facilities. Their products were developed in part by funding provided by DOE and the Corps of Engineers, as well as private sources.
- In a competitive solicitation, DOE accepted proposals for advanced turbine designs from Voith Siemens, Alstom, American Hydro, and General Electric Co., all of which are ready for field verification and testing to demonstrate improved environmental performance.
- Flash Technology is developing strobe lighting systems to force fish away from hydropower intakes and to avoid entrainment mortality in turbines. Implementation at more sites may allow improved environmental performance with reduced spillage.

Market Context

- Advanced hydropower products can be applied at more than 80% of existing hydropower projects (installed conventional capacity is now 78 GW); the potential market also includes 15-20 GW at existing dams (i.e., no new dams required for development) and more than 30 GW of undeveloped hydropower.
- Retrofitting advanced technology and optimizing system operations at existing facilities would lead to at least a 6% increase in energy output – if fully implemented, this would equate to 5 GW and 18,600 GWh of new, clean energy production.

2.3.11 GEOTHERMAL ENERGY

Technology Description

Geothermal energy is heat from within the Earth. Hot water or steam are used to produce electricity or applied directly for space heating and industrial processes. This energy can offset the emission of carbon dioxide from conventional fossil-powered electricity generation, industrial processes, building thermal systems, and other applications.

System Concepts

- Geophysical, geochemical, and geological exploration locates resources to drill, including highly permeable hot reservoirs, shallow warm groundwater, hot impermeable rock masses, and highly pressured hot fluids.
- Well fields and distribution systems allow the hot fluids to move to the point of use, and afterward back to the earth.
- Utilization systems may apply the heat directly or convert it to another form of energy such as electricity.

Representative Technologies

- Exploration technologies identify geothermal reservoirs and their fracture systems; drilling, reservoir testing, and modeling optimize production and predict useful lifetime; steam turbines use natural steam or hot water flashed to steam to produce electricity; binary conversion systems produce electricity from water not hot enough to flash.
- Direct applications use the heat from geothermal fluids without conversion to electricity.
- Geothermal heat pumps use the shallow earth as a heat source and heat sink for heating and cooling applications.
- Coproduction, the recovery of minerals and metals from geothermal brine, is being pursued. Zinc is recovered at the Salton Sea geothermal field in California.

Technology Status/Applications

- With improved technology, the United States has a resource base capable of producing up to 100 GW of electricity at 3¢-5¢/kWh.
- Hydrothermal reservoirs are being used to produce electricity with an online availability of up to 97%; advanced energy-conversion technologies are being implemented to improve plant thermal efficiency.
- Direct-use applications are successful throughout the western United States and provide heat for space heating, aquaculture, greenhouses, spas, and other applications.
- Geothermal heat pumps continue to penetrate markets for heating/cooling (HVAC) services.

Current Research, Development, and Demonstration

RD&D Goals

- By 2010, make geothermal cost effective at 3¢-5¢/kWh

RD&D Challenges

- Develop improved methodologies for predicting reservoir performance and lifetime.
- Find and characterize underground fracture permeability and develop low-cost, innovative drilling technologies.

- Reduce capital and operating costs and improve the efficiency of geothermal conversion systems.
- Develop and demonstrate technology for enhanced geothermal systems that will allow the use of geothermal areas that are deeper, less permeable, or dryer than those currently considered as reserves.

RD&D Activities

- DOE Office of Energy Efficiency and Renewable Energy promotes collaborations among laboratories, universities, states, and industry. Industry provides access to operating fields and well data, equipment and geothermal materials, and matching funds. Related activities are supported by DOE Office of Fossil Energy and Office of Science.

Recent Progress

- The DOE Geothermal Program sponsored research that won two R&D 100 Awards in 2003: Acoustic Telemetry Technology, which provides a high speed data link between the surface and the drill bit; and Low Emission Atmospheric Monitoring Separator, which safely contains and cleans vented steam during drilling, well testing, and plant start-up.
- A second pipeline to carry replacement water has been completed through the joint efforts of industry and Federal, state, and local agencies. This will increase production and extend the lifetime of The Geysers Geothermal Field in California. The second pipeline adds 85 MW of capacity.

Commercialization and Deployment Activities

- Costs at the best sites are competitive at today's energy prices – and investment is limited by uncertainty in prices; lack of new, confirmed resources; high front-end costs; and lag time between investment and return.
- Improvements in cost and accuracy of resource exploration and characterization can lower the electricity cost; demonstration of new resource concepts, such as enhanced geothermal systems, would allow a large expansion of the U.S. use of hydrothermal when economics become favorable.

Market Context

- Hydrothermal reservoirs have an installed capacity of about 2,400 MW electric in the United States and about 8,000 MW worldwide. Direct-use applications have an installed capacity of about 600 MW thermal in the United States. About 300 MW electric are being developed in California, Nevada, and Idaho.
- Geothermal will continue production at existing plants (2.2 GW) with future construction potential (100 GW by 2030). Direct heat will replace existing systems in markets in 19 western states.
- By 2015, geothermal should provide about 10 GW, enough heat and electricity for 7 million homes; by 2020, an installed electricity capacity of 20,000 MW from hydrothermal plants and 20,000 MW from enhanced geothermal systems.

2.4 NUCLEAR FISSION

2.4.1 EXISTING PLANT RESEARCH AND DEVELOPMENT

Technology Description

Currently, 103 commercial nuclear power plants generate 20% of U.S. electricity – with about 100 GWe installed capacity – emitting no greenhouse gases (GHGs). Through the Nuclear Energy Plant Optimization (NEPO), DOE is working with the nuclear industry to apply new technology to nuclear and nonnuclear equipment in existing plants, enabling them to produce more electricity by optimizing their operating lifetimes. If not renewed, most current nuclear power plant licenses will expire between 2005 and 2030. If these plants are shut down and replaced with fossil-based generation, CO_2 emissions will *increase* by more than 160 million metric tons carbon per year (MMTC/yr) by 2030 (assuming 208 gC/kWh). Extending the lifetimes and optimizing the generation of these plants for 20 more years will avoid more than 3,200 MMTC through several years beyond 2050.

The goal of this area of R&D is to increase the efficiency, reliability, and power generation of existing nuclear power plants; and to help make the economic and clean air benefits of the plants available through current and renewed license terms. In 2003, 16 nuclear units have received approval to extend their operating licenses to 60 years; 34 others have filed or announced their intent to file for license extensions; and most, or all, of the remaining plants are expected to follow suit.

System Concepts

- Improve availability and maintainability of nuclear plants.
- Provide technology to predict and measure the extent of materials damage from plant aging.
- Operate plants at higher power levels, based on more accurate measurement and knowledge of safety margins, reduced consumption of onsite electrical power, and power uprates.

Representative Technologies

- Prediction and monitoring of stress-corrosion cracking of reactor internals and steam generators, materials-cladding processes.
- Advanced technologies for online condition monitoring of conventional equipment (pumps, motors, valves, etc.) to minimize production losses from unplanned outages.
- Replacement of aging, hard-to-maintain safety system instrumentation with easy-to-maintain advanced, digital electronics.
- Materials measurement and diagnostic technologies to determine the condition and fitness of aged materials.
- Advanced core loading strategies; nuclear fuel and cladding research.
- Advanced power generation technologies to increase electrical output.

Technology Status/Applications

- Current technology does not adequately determine residual life; overly conservative margins may result in premature shutdown or refurbishment.
- Replacing major components (e.g., steam generators) may be prohibitively expensive; better techniques are needed.
- Some in-service valve testing technology is in place, but current technology fails to efficiently detect a significant number of failures.
- Technology development for condition monitoring is required for application to nuclear plants.
- Technology advances are needed to achieve future extended power uprates.

Current Research, Development, and Demonstration

RD&D Goals
- Increase electrical generation capability from existing plants by achieving continued improvement in average industry capacity factors and developing break-through technologies for long-term operation.
- Address the long-term effects of component aging; optimize efficiency; and improve plant reliability, availability, and productivity while maintaining high levels of safety.

RD&D Challenges
- Development and demonstration of new technologies to allow future extended power uprates.
- Complete the DOE/nuclear industry R&D program for research on existing nuclear plant life extension and generation optimization technologies.

RD&D Activities
- The department and the electric utility industry's Electric Power Research Institute (EPRI) developed the *Joint DOE-EPRI Strategic Research and Development Plan to Optimize U.S. Nuclear Power Plants* to help the Federal government and private sector jointly identify, prioritize, and execute R&D. The plan, first issued in March 1998 and later updated in October 2000, is based on input from utilities, DOE national laboratories, the Nuclear Regulatory Commission (NRC), and other key stakeholders. Research funded under the NEPO program is consistent with this joint strategic plan.
- A previous cooperative research and development agreement between DOE's Office of Nuclear Energy, Science, and Technology; and the Electric Power Research Institute started development of advanced electronics to replace Westinghouse safety-system components.
- Activities to improve monitoring of the condition of nuclear power plants are supported by DOE's Offices of Nuclear Energy, Science, and Technology; and the Nuclear Regulatory Commission.
- Advanced technologies are being applied to existing light water reactors and aging research, funded by DOE.

Recent Progress
- An initial industry decision was made to commercialize DOE electronics technology for replacing Westinghouse safety system components.
- Nonintrusive evaluation of pressurized water reactor accumulator discharge check valves has reduced testing time and improved reliability.
- Hydrogen water chemistry is used in boiling water reactors to control stress-corrosion cracking.
- Electrical cable condition monitoring and aging management techniques.

Commercialization and Deployment Activities
- The NEPO program has made significant progress toward addressing many of the material aging and generation optimization issues that have been identified as the key long-term issues facing current operating plants. Examples of recent results from the NEPO program include the development of new electrical cable monitoring techniques for improved prediction of cable lifetimes; and the development of techniques to qualify smart transmitters to replace existing analog transmitters, which are less accurate and are difficult to maintain.
- Advanced diagnostic techniques are gaining wider acceptance for evaluating the status of safety-related equipment.
- Successful technology may not be sufficient to extend the life of all plants if adverse regulatory or economic factors dominate.
- DOE/industry Sustainable Electric Partnership Agreement provides a basis for DOE/industry cooperation and ensures commercial deployment.
- DOE/industry NEPO program partnership provides another basis to ensure commercial deployment of R&D successes.

Market Context
- Technologies to support improved operations and life extension have enhanced the economics of existing nuclear power plants and thus increased their market value.

2.4.2 NEXT-GENERATION FISSION ENERGY SYSTEMS

Technology Description

Electricity from nuclear power generates no greenhouse gas emissions. To the extent that next-generation nuclear fission energy systems can address prevailing concerns, nuclear power can continue to be an important part of a greenhouse gas emissions-free energy portfolio. Although evolutionary light water reactors of standardized design are now available – and have received Nuclear Regulatory Commission design certification and been constructed on schedule in Japan and South Korea – newer nuclear energy systems in the long term need to offer significant advances in the areas of sustainability, proliferation resistance and physical protection, safety, and economics. These newer nuclear energy systems are required to replace or add to existing light water reactor capacity and can be available starting in 2015.

To develop these next-generation systems, DOE has initiated the Generation IV Nuclear Energy Systems Initiative. Generation IV is an international effort, with participation by Argentina, Brazil, Canada, France, Japan, Republic of Korea, Republic of South Africa, Switzerland, the United Kingdom, and the United States. The *Generation IV Nuclear Energy Systems Technology Roadmap* was completed in December 2002. The completed roadmap has identified the six most promising fission energy systems for potential further development. In FY 2003, DOE and its international partners initiated preconceptual design studies, fuel and materials development, and energy conversion development on promising systems of interest, which will lead to demonstration and eventual deployment (with industry and international participation) of one or more systems.

System Concepts

- Advanced fission reactors and fuel cycles that will reduce the potential for proliferation of nuclear materials, provide economical electricity generation, and contribute to hydrogen generation, with minimal waste products.

Representative Technologies

- Gas-Cooled Fast Reactor (GFR).
- Lead-Cooled Fast Reactor (LFR).
- Molten Salt Reactor (MSR).
- Sodium-Cooled Fast Reactor (SFR).
- Supercritical-Water-Cooled Reactor (SCWR).
- Very-High-Temperature Reactor (VHTR).

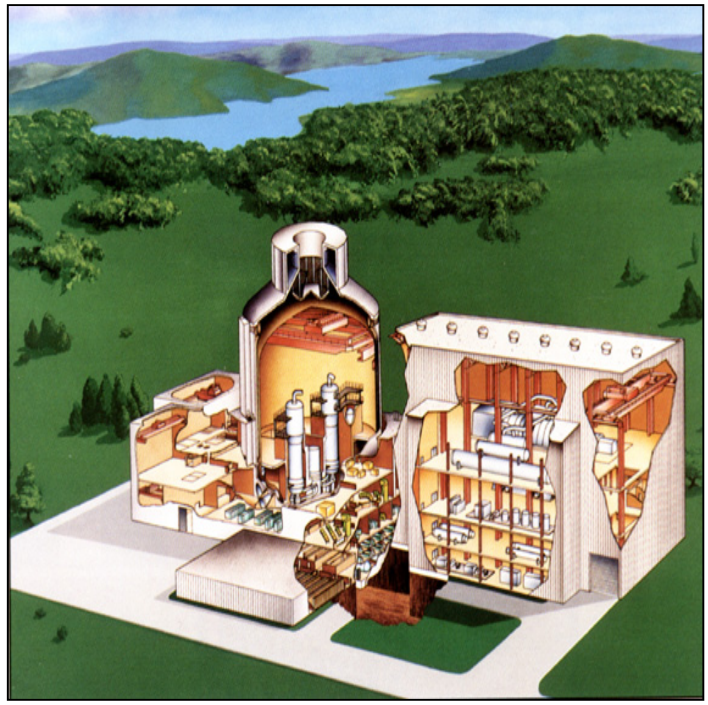
Technology Status/Applications

- Advanced fission reactors and fuel cycles: development is at advanced stage; demonstration is incomplete.
- High-temperature gas-cooled reactor development is focused on high-conversion efficiency through direct use of the high-temperature gaseous reactor coolant to power a gas turbine driving a generator (i.e., direct conversion), also capable of high-efficiency hydrogen production through electrolysis or chemical processes.
- Liquid metal-cooled reactors (both sodium and lead) have been successfully operated worldwide. Safety performance has been demonstrated, but economic performance needs improvement.
- Technologies for advanced fuel recycle and remote fuel refabrication have been developed in the laboratory, and some elements have advanced to pilot scale.
- Nuclear-assisted hydrogen production by means of thermochemical cracking of water is at the preconceptual design stage, requiring extensive development.
- Other advanced fission systems are at a preconceptual stage, requiring extensive development and irradiation testing of new fuel forms and high-temperature materials.
- Direct-cycle turbine technology requires development and demonstration.

Current Research, Development, and Demonstration
RD&D Goals • Generation IV research is focusing on reactors and fuel cycles that are safer, more economically competitive, more resistant to proliferation, produce less waste, and make better use of the energy content in uranium. **RD&D Challenges** • Demonstrate technology for advanced concepts. • Develop proliferation-resistant fuel-cycle concepts. • Develop safety, waste, and proliferation aspects of advanced fission reactors. • Conduct comprehensive R&D on advanced fission reactor concepts, relying heavily on international collaboration. **RD&D Activities** • Federally funded development of advanced reactors and fuel cycles has been resumed in the United States, through the Nuclear Energy Research Initiative, the Generation IV Nuclear Energy Systems Initiative, and the Advanced Fuel Cycle Initiative. • Advanced used fuel treatment technologies are under development through the Advanced Fuel Cycle Initiative.
Recent Progress
• Advanced light water reactors have received design certification from the Nuclear Regulatory Commission. • An advanced boiling water reactor, which was built in less than five years, is operating in Japan.
Commercialization and Deployment Activities
• Generation IV Nuclear Energy Systems are projected to be ready for commercial deployment in the timeframe of 2015 to 2030. **Market Context** • Indeterminate at this time. Potentially large international and domestic markets.

2.4.3 NEAR-TERM NUCLEAR POWER PLANT SYSTEMS

Technology Description



Electricity from nuclear power generates no greenhouse gas emissions. To the extent that deployment of near-term nuclear power plants can address prevailing concerns, nuclear power can continue to be an important part of a greenhouse gas emissions-free energy portfolio. In order to enable the deployment of new, advanced nuclear power plants in the United States in the relatively near-term – by the end of the decade – it is essential to demonstrate the untested federal regulatory and licensing processes for the siting, construction, and operation of new nuclear plants. In addition, other major obstacles (including the initial high capital costs of the first few plants and the business risks resulting from this and the regulatory uncertainty) must be addressed. Research and development on near-term advanced reactor concepts that offer enhancements to safety and economics is needed to enable these new technologies to be competitive in the deregulated electricity market, and support energy supply diversity and security.

The *Near-Term Deployment Roadmap* was issued in October 2001 and advises DOE on actions and resource requirements needed to support deployment of new nuclear power plants by 2010. The primary focus of the roadmap is to identify the generic and design-specific gaps to near-term deployment, to identify those designs that best promise to meet the needs of the marketplace, and to propose recommended actions that would close gaps and otherwise support deployment. This includes, but is not limited to, actions to achieve economic competitiveness and timely regulatory approvals.

System Concepts

- Advanced fission reactor designs that are currently available or could be made available with limited additional work to complete design development and deployment in the 2010 timeframe.

Representative Technologies

- Certified Advanced Light Water Reactor designs: ABWR, AP600, System 80+.
- Enhancements to certified designs with some engineering work already completed: AP1000, ESBWR.
- Gas reactor designs with significant engineering work already completed: PBMR, GT-MHR.
- Proposed designs from overseas with significant potential for near-term deployment in the United States: SWR-1000, ACR-700.

Technology Status/Applications

- All near-term deployment designs are well-defined concepts in varying stages of development. Most still need significant detailed engineering development and/or regulatory approval.

Current Research, Development, and Demonstration

RD&D Goals

- Demonstration of the untested regulatory processes for Early Site Permit (ESP) and combined Construction and Operating License (COL) processes.
- Industry decision to order a new nuclear power plant by 2005.
- Deployment of one or more new nuclear power plants in the 2010 timeframe.

RD&D Challenges

- Most R&D challenges remaining for near-term deployment options relate to advanced light water and gas reactors, including fuel development, characterization, manufacture, testing and regulatory acceptance; power conversion system design and testing, including resolution of uncertainties regarding materials, reliability, and maintainability; and fission reactor internals design and verification.

- Support resolution of the technical, institutional, and regulatory barriers to the deployment of new nuclear power plants in the 2010 timeframe, consistent with recommendations in *Near-Term Deployment Roadmap.*
- In cooperation with the nuclear industry, demonstrate the untested regulatory processes for Early Site Permit and combined Construction and Operating Licenses to reduce licensing uncertainties and attendant financial risk to the licensees.
- Provide for conduct of R&D to enable finalization and NRC certification of those advanced nuclear power plant designs that the U.S. power generation companies are willing to build.
- Provide for development and demonstration of advanced technologies to reduce construction time for new nuclear power plants and to minimize schedule uncertainties and associated costs for construction.

RD&D Activities

- Demonstration of regulatory processes for Early Site Permit and combined Construction and Operating Licenses.
- Development and NRC certification of advanced nuclear plant designs.
- Gas reactor fuel development and qualification.

Recent Progress

- Three near-term deployment designs have been certified by the Nuclear Regulatory Commission.
- The Advanced Boiling Water Reactor has been deployed successfully in Japan; Advanced Boiling Water Reactors are under construction in Taiwan.
- Three U.S. utilities plan to apply for NRC approval of sites for new nuclear plants.
- Reactor vendors are exploring NRC certification of advanced reactor concepts.
- The three cost-shared Early Site Permit (ESP) demonstration projects initiated with industry in FY 2002 continued with the plan for completed ESP applications to be submitted by the power-generating companies to NRC for review and approval.
- A nuclear power plant project cost and construction assessment to independently evaluate the cost, schedule, and construction methods of advanced nuclear plant designs, as well as identify promising improvements to the construction methods and techniques to support new nuclear power plant deployment in the 2010 timeframe was initiated.
- The advanced gas-cooled reactor fuel development and qualification activities initiated in FY 2001 continued.
- Fuel fabrication process development in laboratory-scale equipment as well as manufacture and characterization of the demonstration fuel, which will undergo irradiation testing, was initiated.

Commercialization and Deployment Activities

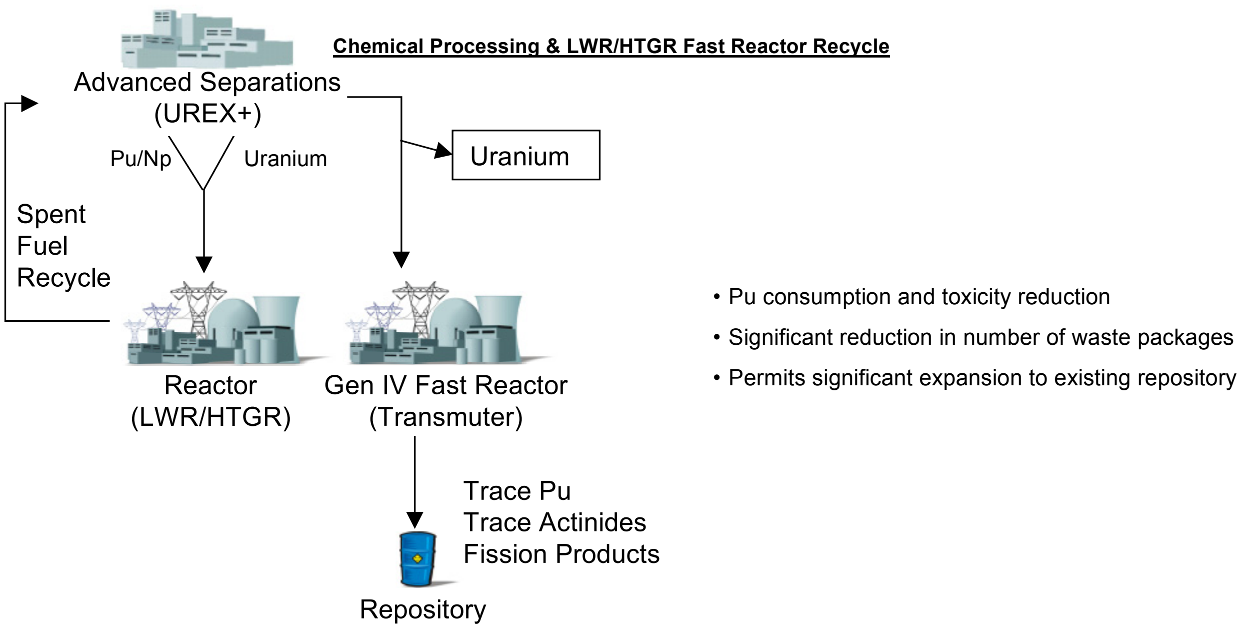
- At least two designs and perhaps more can be commercialized in the United States in the 2010 timeframe. Achieving this goal will require a major effort by industry and DOE to work together to resolve open issues and to share the one-time costs of closing both generic and design-specific gaps.

Market Context

- The focus of the market is in the United States. Due to the uncertainty regarding the impacts of deregulation, designs in the 100-300 MW_e range and the 1,000 MW_e-plus range are both required.

2.4.4 ADVANCED NUCLEAR FUEL CYCLE PROCESSES

Technology Description



Electricity from nuclear power generates no greenhouse gas emissions. To the extent that deployment of advanced nuclear fuel cycle processes can contribute to the success of next-generation fission systems, nuclear power can continue to be an important part of a greenhouse gas emissions-free energy portfolio. Current nuclear fission reactors operate in the United States with once-through fuel cycles and produce significant quantities of used or "spent" nuclear fuel. Several current designs for future fission reactors also rely on once-through fuel cycles. The planned disposal of spent nuclear fuel is in geologic repositories, and the accumulation of spent nuclear fuel raises public concerns about radiotoxicity, dose, and proliferation risk. Once-through fuel cycle technology also does not make optimal use of natural uranium resources. DOE activities under the Advanced Fuel Cycle Initiative aim at developing the technologies needed to dramatically reduce the waste stream from nuclear fission, thus lowering the potential environmental consequences, reducing the cost of geologic disposal, reducing the technical need for a second repository, and making better use of natural resources. These activities include transmutation research, in which the actinides and selected fission products in spent nuclear fuel are separated, stored, and potentially formed into fuels that can be bombarded by neutrons in reactors or accelerator driven systems, causing them to fission or transmute into shorter-lived or stable elements/isotopes. In the long term, these technologies may be assembled into advanced Generation IV nuclear systems that could result in decreased amounts of waste, while generating substantial amounts of energy.

System Concepts

- Advanced nuclear systems (fission reactors and accelerator-driven systems) that aim to reduce the lifetime of the waste from current-generation fission reactors to short times.
- Advanced nuclear systems that aim to extract the full energy potential of the spent nuclear fuel from current fission reactors, while reducing or eliminating the potential for proliferation of nuclear materials and technologies, and reducing the amount of waste produced.

Representative Technologies

- Spent-fuel treatment technologies that are proliferation resistant.
- Advanced fuel types for waste transmutation.
- Advanced fuel types for sustained nuclear energy.
- Accelerator-driven systems for rapid waste transmutation.
- Advanced reactors for sustained nuclear energy.

Technology Status/Applications

- Advanced fuel-cycle development has reached the laboratory scale-demonstration stage in some cases.
- Transmutation fuels are in early R&D stages.
- Development of accelerator-driven systems is at the preliminary R&D stage.

Current Research, Development, and Demonstration

RD&D Goals

- Prove design principles of spent-fuel treatment and transmutation technologies.
- Demonstrate the fuel and separation technologies for waste transmutation.
- Deploy Generation IV advanced fast spectrum reactors that can transmute nuclear waste.

RD&D Challenges

- Demonstrate performance of advanced fuel cycles.
- Demonstrate performance of advanced transmutation fuels.
- Demonstrate technology for advanced fission reactor concepts.
- Demonstrate feasibility and technology for accelerator-driven systems.

RD&D Activities

- Continued development and demonstration of aqueous and electrometallurgical spent-fuel treatment technologies.
- Development of transmutation fuels for Generation IV reactor systems.
- Development of technologies for accelerator-driven systems.

Recent Progress

- Hot demonstration of the UREX (Uranium Extraction) aqueous spent fuel treatment process.

Commercialization and Deployment Activities

- Disposal of spent nuclear fuel is a government activity in the United States. Similar spent-fuel treatment and transmutation technology development programs exist in France, Japan, and the United States. Development of treatment and transmutation technologies for use with advanced Generation IV fuel cycles will increase the acceptability of nuclear energy.
- Advanced Fuel Cycle Initiative has the potential to decrease the quantity and toxicity of nuclear waste, possibly eliminating the need for a second geologic repository.

Market Context

- Technologies to improve spent-fuel disposition increase the value of keeping existing nuclear power plants online as well as increase the likelihood for expanded new nuclear power capacity.

2.5 NUCLEAR FUSION

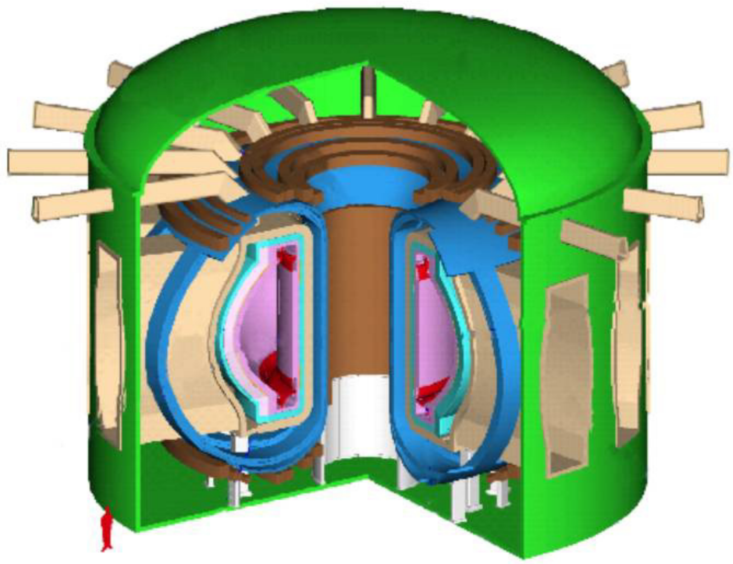
2.5.1 FUSION POWER

Technology Description

Magnetic fields or particle inertia are used to confine a hot plasma to produce fusion energy from deuterium/tritium fuel. Deuterium is abundantly available from water, and tritium can be produced from lithium within the fusion plant. The energy of the fusion reactions could be used to generate electricity and/or hydrogen at central power plants with no greenhouse gas emissions. Due to anticipated low fuel costs, electricity produced from fusion at off-peak hours could also be used to generate hydrogen at off-site fueling stations.

System Concepts

- Strong magnetic fields produced by, in some cases, superconducting coils confine plasmas with temperatures of several hundred million degrees Celsius. Twenty percent of the heat from the fusion reactions remains in the fuel to sustain its high temperatures; the rest is carried out by neutrons and is absorbed in a surrounding blanket that serves both as a heat source to produce power and as a medium for producing the tritium.
- Compressed fuel pellets ignite and burn, producing repetitive pulses of heat and neutrons in a reaction chamber. For some approaches, flowing molten salt walls in the chamber can serve as blankets.



Pictured above is the fusion-specific portion of a 1,000 MWe power plant, the result of a conceptual design study done to explore the scientific and technological issues associated with the possible reactor embodiments of fusion.

Representative Technologies

- Large, high-current-density superconducting magnets; deuterium ion beams (energies of 100–1000 keV); millimeter-wave high-power microwaves; high-power, radio-frequency sources and launchers; and particle fueling apparatus for magnetic fusion.
- Heavy ion beam accelerators, diode-pumped solid-state lasers or krypton-fluoride gas lasers, target fabrication technologies, and advanced chamber technologies are required for inertial fusion.
- Structural materials with low-activation properties will be required to fulfill the ultimate potential of fusion devices. Tritium generation and heat-recovery systems are other common nuclear system technologies required for both magnetic and inertial fusion.

Technology Status/Applications

- Moderate-sized magnetic confinement fusion experiments, with plasmas at temperatures needed for power plants, have produced more than 10 MW of fusion power, and more than 20 MJ per pulse.
- A facility is being designed through an international project, which will support scientific experiments and engineering tests for magnetic fusion burning plasma that is near commercial power plant scale (500 MW of fusion power, 500-2500 sec pulse length).
- The physics of subignited targets has been advanced with glass lasers, and underground test results have resolved certain feasibility questions of high gain for power plants.
- The target physics of ignition and high gain, using glass lasers, are objectives of the National Ignition Facility, now under construction.
- Dramatic advances have been made in the understanding and control of magnetically confined plasmas, allowing improved designs of confinement systems and increased confidence in extrapolations to power plant scale.

Current Research, Development, and Demonstration

RD&D Goals

- Accelerate the advance of scientific understanding of fusion plasmas.
- Determine the approaches and configurations for both magnetic and inertial fusion that will take the best advantage of the newest scientific insights.
- Establish the technological basis for an efficient, low-cost ion beam using an induction accelerator; develop high-average-power, durable and cost-effective solid-state and gas laser systems; and demonstrate useful gain from compression and burn of National Ignition Facility targets.
- Qualify low-activation materials that meet structural and compatibility criteria.

RD&D Challenges

- Develop magnetic geometries optimal for heat containment that at the same time (1) minimize technical complexity, (2) maximize fusion power density for good economics, and (3) operate in a continuous mode.
- Understand target requirements for high gain; reduce the development cost of candidate drivers; and develop long-life chambers and low-cost pellet targets.
- Develop low-activation materials that also meet structural and compatibility criteria.

RD&D Activities

- Coordinated worldwide magnetic fusion experimental and theoretical efforts center on configuration improvements. Fusion technology and materials development is also being pursued internationally.
- The United States has joined Europe, Japan, Canada, China, and Russia to develop plans for construction of a magnetic fusion-burning plasma science and engineering test facility (called ITER), which is to be capable of operation for 500–2,500 sec with fusion power level of 500 MW.
- Inertial fusion efforts are concentrated on driver, chamber, and pellet manufacturing technologies.
- The National Ignition Facility project, funded by the National Nuclear Security Administration, will provide information on high-gain, single-shot pellet burn experiments for inertial fusion energy.

Recent Progress

- More than 10 MW of fusion power was produced in magnetically confined plasma for about 1 second, using deuterium-tritium fuel.
- Improved understanding of plasma stability and turbulence has led to improved plasma performance in existing facilities and improved configuration designs for the future.
- Results from underground tests in the United States have resolved fundamental questions of feasibility of high gain for efficient fusion power plants.
- Results from the NOVA laser at Lawrence Livermore National Laboratory have confirmed the validity of computer models used to predict ignition and gain in the National Ignition Facility.
- Vanadium alloys show promise as a low-activation structural material in magnetic fusion devices, and liquid walls for inertial fusion chambers promise to avoid life-limiting radiation damage.

Commercialization and Deployment Activities

- Large central-station, electrical-generating plants could be commercialized late in the second quarter of the 21st century; the timescale depends on a sustained international effort and success in that R&D.
- Fusion power plants would replace aging and polluting power generators and fill a potential multibillion-dollar market sector.
- Many technologies developed for fusion are used in the commercial sector. Prominent are plasma processing for etching semiconductor chips, hardening of metals, thin-film deposition, and plasma spraying and lighting applications. Other applications from this research include medical imaging, heat-removal technologies, destruction of toxic waste, X-ray lithography and microscopy, micro-impulse radar, precision laser cutting, large-scale production of precision optics, and high-power microwave and accelerator technologies.
- Emphasize fusion science, concept improvement and alternative approaches, and development of materials.
- Recognize increasing importance of international cooperation as a means of building major facilities.

Market Context

- Large potential market in the United States and throughout the world.